Physics of neutralization of intense charged particle beam pulses by a background plasma

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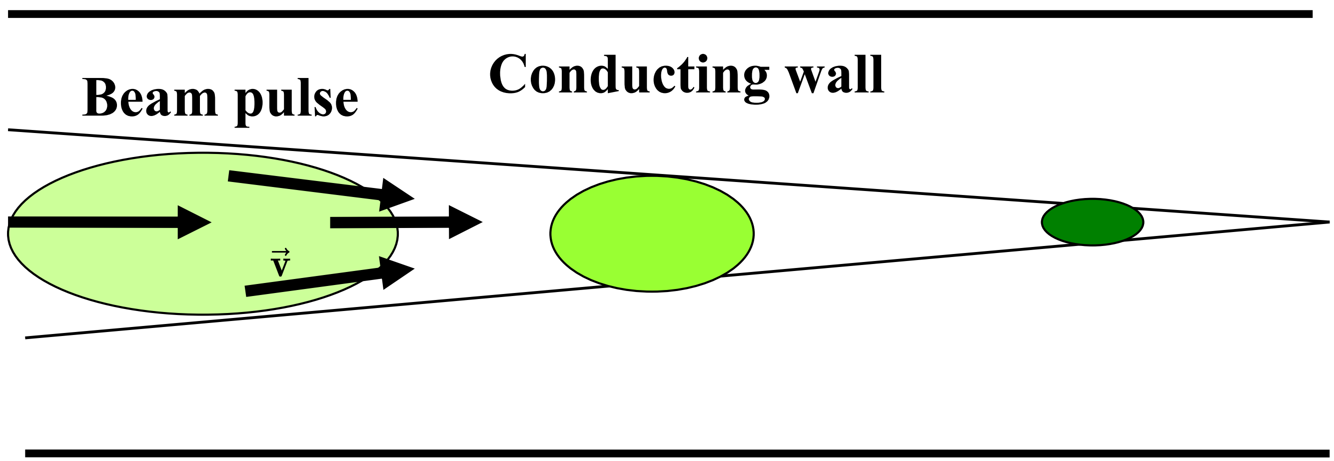
Voss Scientific

Neutralized drift compression can reach 300x300 = 10^5 combined longitudinal and transverse compression of ion beam pulse.



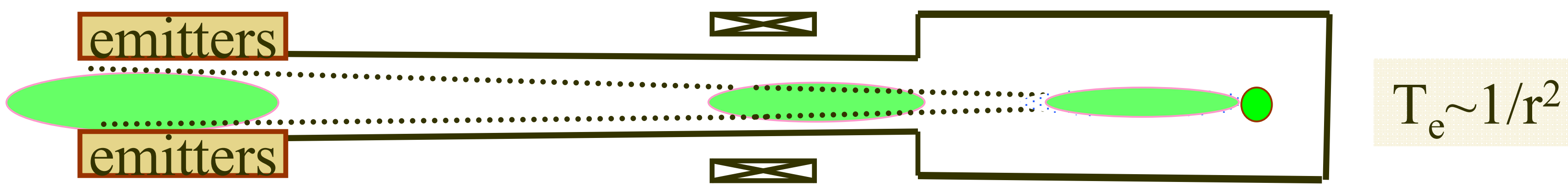
Beam self-potential typically increases from 100V to 10kV and needs to be effectively neutralized to achieve tight spot.

Methods to neutralize intense ion beam

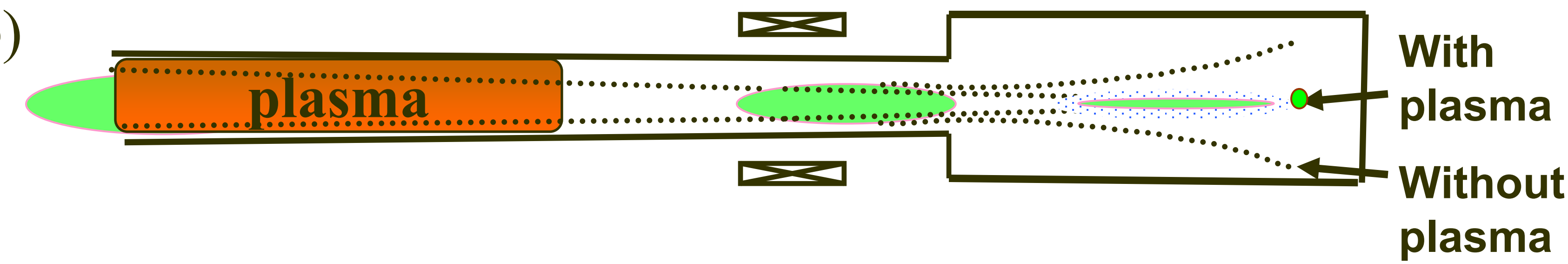
It's better to light a candle than curse the darkness:
It is better to use electrons than fight their presence.

(a) emitters, (b) plasma plug, and (c) plasma everywhere

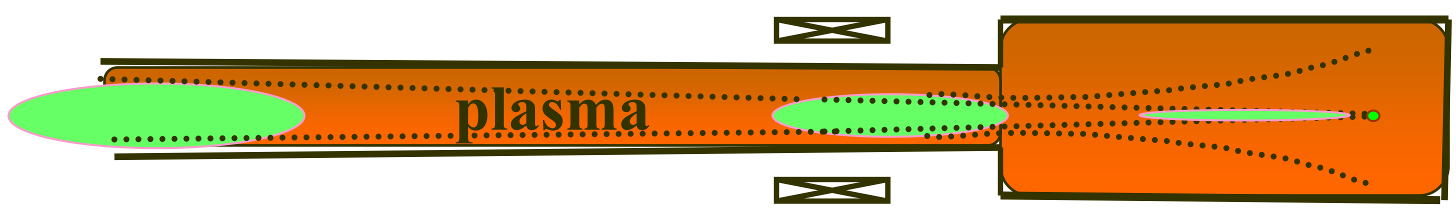
(a)



(b)

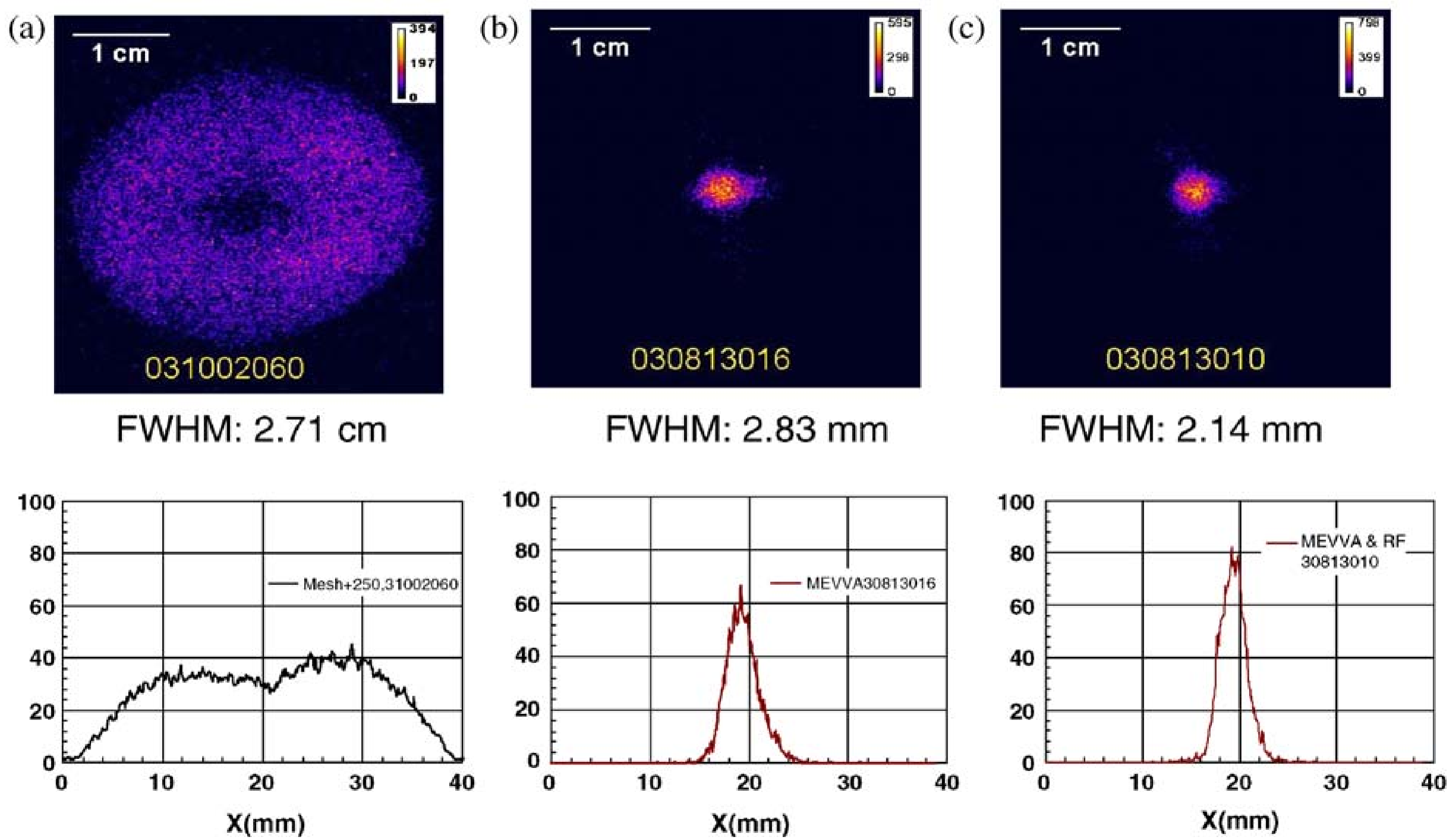


(c)



Plasma plug cannot provide sufficient neutralization compared with plasma filling entire volume.

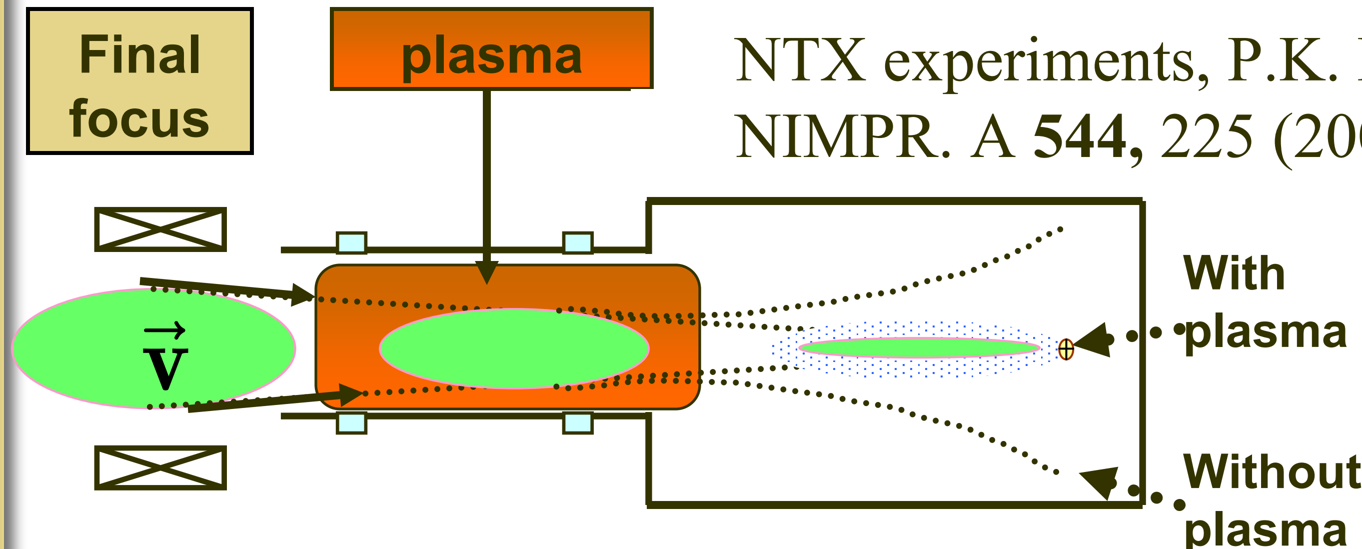
Beam images at the focal plane non-neutralized (a), neutralized plasma plug (b), and volumetric plasma everywhere (c).



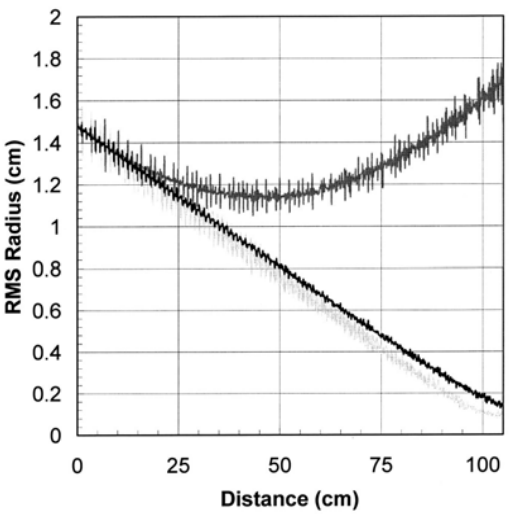
P.K. Roy et al, NIMPR A **544,** 225 (2005).

Radial Compression requires degree of neutralization >99%.

NTX experiments, P.K. Roy et al, NIMPR. A **544,** 225 (2005).

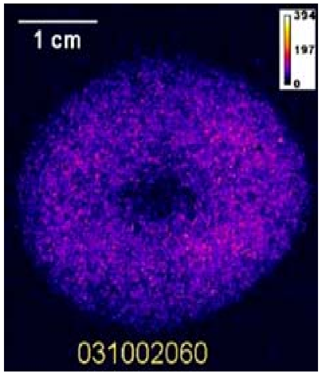


Calculated beam radius as function of distance

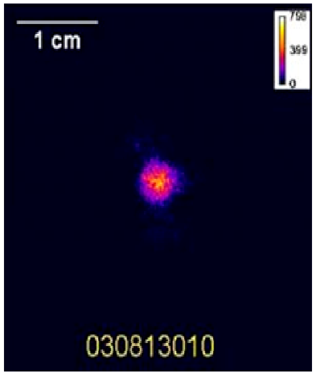


Beam images at the focal plane 24mA, 254 keV K+ ion beam: (a) without plasma (b) with plasma.

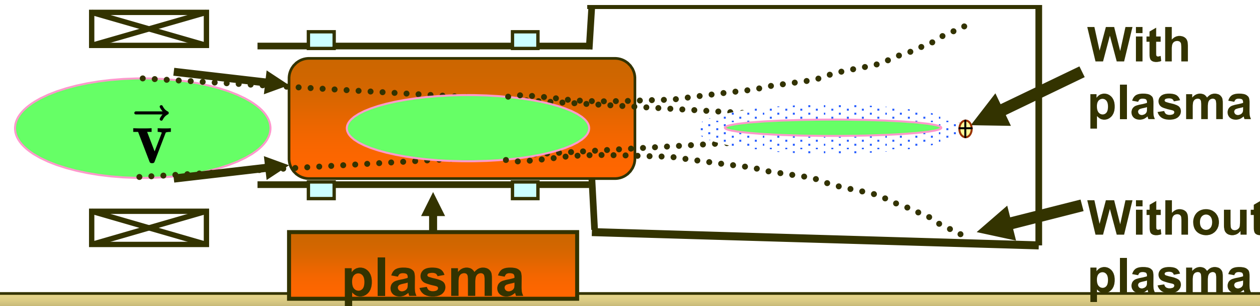
(a)



(b)



Outline



Neutralization of intense charged particle beam pulses by a background plasma

- Steady state
  - Degree of charge neutralization
  - Degree of current neutralization
- Effects of gas ionization
- Effects of applied magnetic field
  - Solenoidal field along beam propagation
  - Dipole field across beam propagation
- Transients (entry to and exit from plasma)

To determine degree of neutralization electron fluid and *full* Maxwell equations are solved numerically and analytically.

$$\frac{\partial \vec{p}_e}{\partial t} + (\vec{V}_e \bullet \nabla)\vec{p}_e = -\frac{e}{m}(\vec{E} + \frac{1}{c}\vec{V}_e \times \vec{B}), \quad \frac{\partial n_e}{\partial t} + \nabla \bullet \left(n_e \vec{V}_e\right) = 0,$$

$$\nabla \times \vec{B} = \frac{4\pi e}{c}\left(Z_b n_b V_{bz} - n_e V_{ez}\right) + \frac{1}{c}\frac{\partial \vec{E}}{\partial t}, \qquad \nabla \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t}.$$

Solved analytically for a beam pulse with arbitrary value of n_b/n_p, in 2D, using approximations: fluid approach, conservation of generalized vorticity.

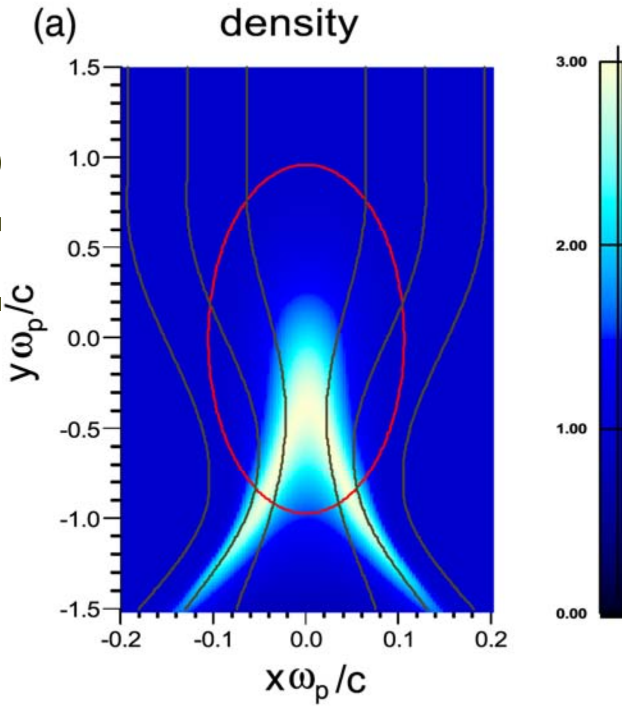
I. Kaganovich, *et al.*, Phys. Plasmas **8**, 4180 (2001); Phys. Plasmas **15**, 103108 (2008); Nucl. Instr. and Meth. Phys. Res. A (NIMPRA) **577**, 93 (2007).

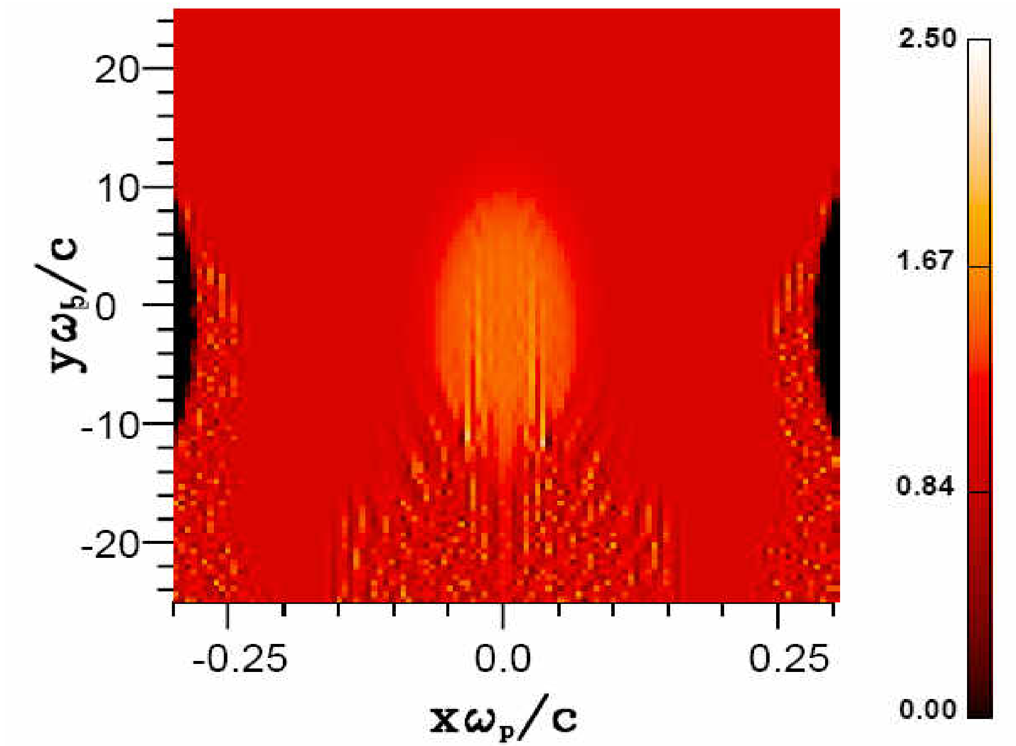
Charge Neutralization

Necessary conditions for good charge neutralization: bunch duration times plasma frequency $\omega_p \tau_b$ >>1.

Color plots of the normalized electron density (n_e/n_p), Red line: ion beam size, brown lines: electron trajectory in beam frame, β_b=0.5, l_b/r_b =10, n_b/n_p=0.5 . $\omega_p \tau_b$: **a) 4 , (b) 60.**

Direction of propagation





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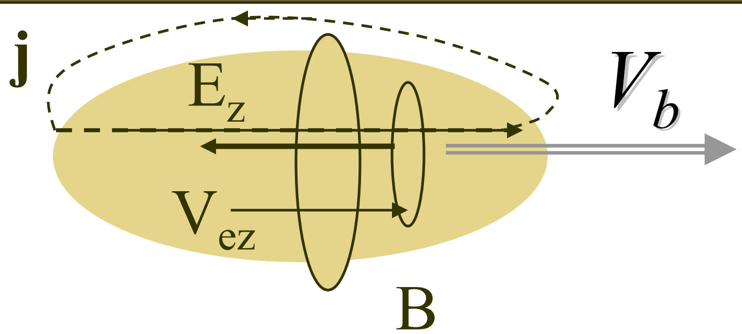
Current Neutralization

Necessary conditions for good current neutralization:

beam radius is large compared to the skin depth $r_b >> \delta_p$.



$$\frac{\partial \int B\,ds}{\partial t} => E_z$$

Alternating magnetic flux generates inductive electric field, which accelerates electrons along the beam propagation*.

For long beams canonical momentum is conserved** $mV_{ez} = \frac{e}{c} A_z$

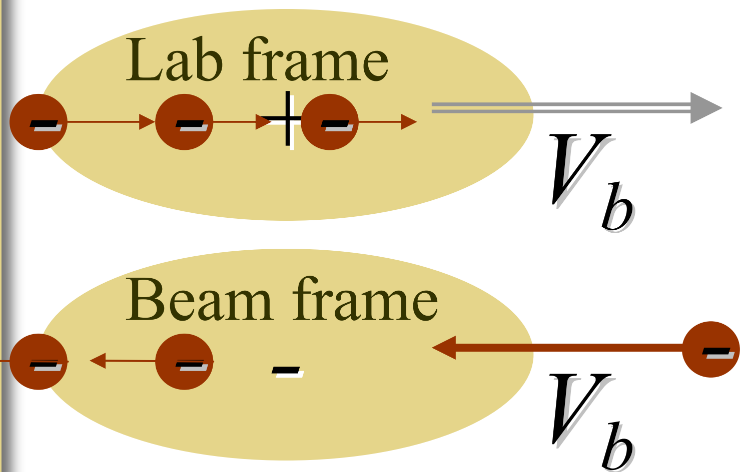
$$\nabla \times \mathbf{B} = \frac{4\pi \mathbf{j}}{c} \qquad -\frac{1}{r}\frac{\partial}{\partial r} r \frac{\partial}{\partial r} V_{ez} = \frac{4\pi e}{mc^2}\left(Z_b n_b V_{bz} - n_e V_{ez}\right).$$

$$r_b^2 > \frac{c^2}{4\pi e^2 n_p / m} \qquad r_b > \delta_p \qquad n_p = 2.5\times 10^{11}\,cm^{-3}\,;\,\delta_p = 1cm$$

* K. Hahn, and E. PJ. Lee, Fusion Engineering and Design **32-33**, 417 (1996)

** I. D. Kaganovich, et al, Laser Particle Beams **20**, 497 (2002).

Self-electric field of the beam pulse propagating through plasma is electrostatic in the beam frame, electromagnetic in the lab frame.



Consider case with $B_\varphi \to 0$ $j_z \to 0$

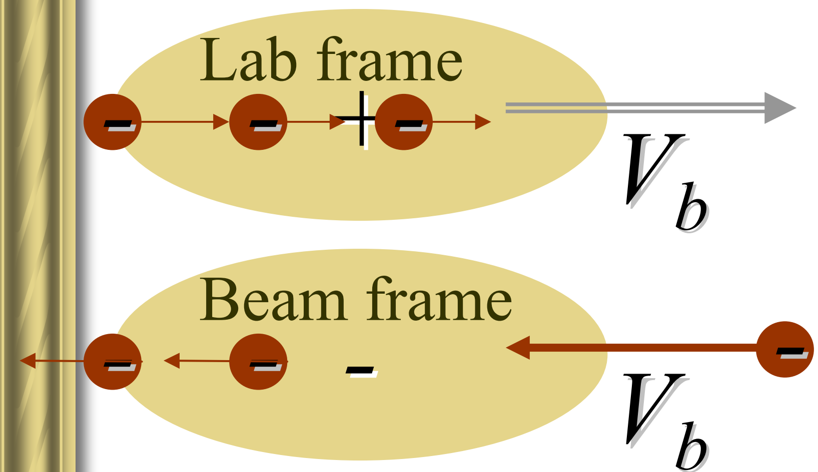
In the lab frame $j_z \to 0\,; n_e V_{ez}^l = Z_b n_b V_{bz}$

In the beam frame; $V_{ez}^b = -V_{bz} + V_{ez}^l$

Steady state => $\mathbf{E}^b = -\nabla \phi^b$

$$eE_z^b = m(V_{bz} - V_{ez}^l)\frac{\partial V_{ez}^l}{\partial z} \Longrightarrow e\phi^b = -m[V_{bz}V_{ez}^l - \frac{1}{2}(V_{ez}^l)^2] \Longrightarrow eE_r^b = m(V_{bz} - V_{ez}^l)\frac{\partial V_{ez}^l}{\partial r}$$

Self-electric field of the beam pulse propagating through plasma is electrostatic in the beam frame, electromagnetic in the lab frame.



Consider case with $B_\varphi \to 0$ $\quad j_z \to 0$

In the lab frame $\quad j_z \to 0\,; n_e V^l_{ez} = Z_b n_b V_{bz}$

In the beam frame; $\quad V^b_{ez} = -V_{bz} + V^l_{ez}$

Steady state => $\mathbf{E}^b = -\nabla\phi^b$

$$eE^b_z = m(V_{bz} - V^l_{ez})\frac{\partial V^l_{ez}}{\partial z} \Rightarrow e\phi^b = -m[V_{bz}V^l_{ez} - \frac{1}{2}(V^l_{ez})^2] \Rightarrow eE^b_r = m(V_{bz} - V^l_{ez})\frac{\partial V^l_{ez}}{\partial r}$$

$\mathbf{F_r = eE^b{}_r}$

$$\boxed{F_r = -mV_b^2\,\frac{1}{n_p}\left|\frac{\partial n_b}{\partial r}\right|}$$

Self-electric field is determined by electron inertia ~ electron mass.

$$mV_{ez} = \frac{e}{c}A_z \Rightarrow B_\phi = -\frac{cm}{e}\frac{\partial V^l_{ez}}{\partial r} \Rightarrow E^l_r = E^b_r + \frac{1}{c}V_{bz}B_\phi \Rightarrow \boxed{eE^l_r = -mV^l_{ez}\frac{\partial V^l_{ez}}{\partial r}}$$

Electric field in the lab frame, $\mathbf{E}^l$ is nonlinear and of different sign than in beam frame! E_z is both frames are the same, so $\mathbf{E}^l$ is not electrostatic.

Results of Theory for Self-Electric Field of the Beam Pulse Propagating Through Plasma

Self-electric field is determined by electron inertia ~ electron mass

$$eE_r = \frac{1}{c} V_{ez} B_\theta = -m V_{ez} \frac{\partial V_{ez}}{\partial r}$$

$$\phi_{vp} = m V_{ez}^{\ 2} / 2e$$

$$V_{ez} \sim V_b n_b / n_p$$

$$\phi_{vp} = \frac{1}{2} m V_b^{\ 2} \left(\frac{n_b}{n_p} \right)^2 = 5eV \left(\frac{n_b}{n_p} \right)^2$$

NTX K^+ 400keV beam φ_b~100V

$$(1-f) = \phi_{vp} / \phi_b = 5\% \left(\frac{n_b}{n_p} \right)^2$$

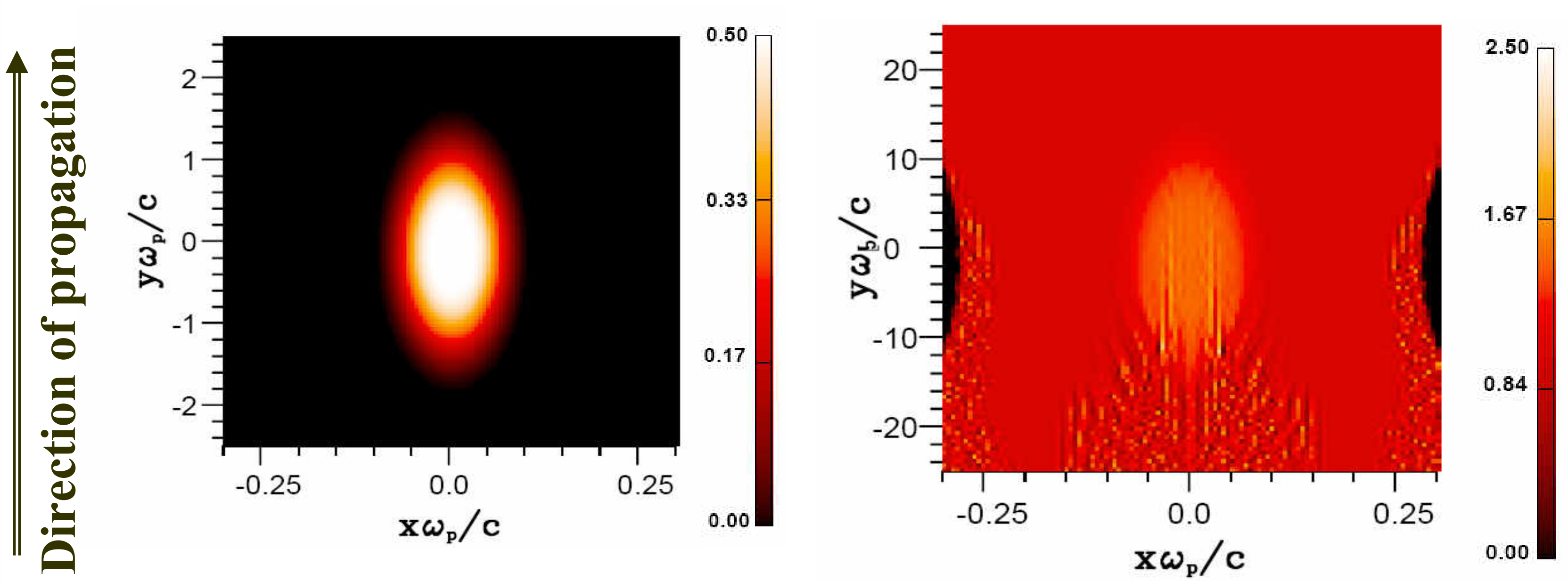
Degree of charge neutralization

Having $n_b \ll n_p$ strongly increases the neutralization degree.

$\mathbf{F_r = e(E_r - V_b B_\varphi / c)}$ $\quad F_r = -m V_b^2 \frac{1}{n_p} \left| \frac{\partial n_b}{\partial r} \right|$

In the Lab frame magnetic force dominates the electrical force and it is focusing!

Beam pulse is well neutralized even if its unneutralized potential $\varphi_b \ll mV_b^2$

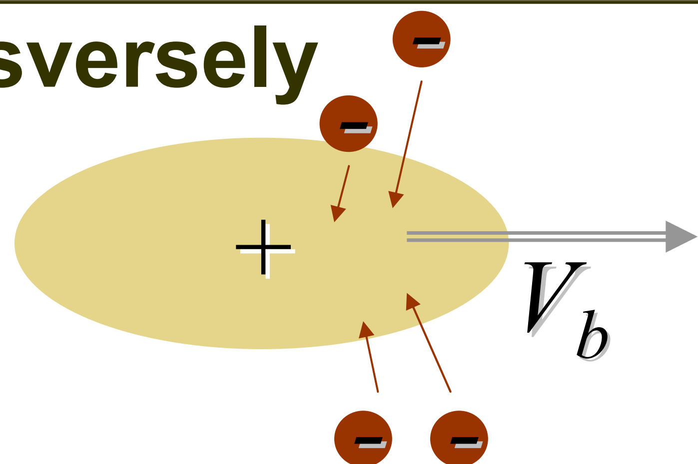


Neutralization of an ion beam pulse. Shown in the figure are color plots of the normalized beam density (n_b/n_p) (left) and the electron density (n_e/n_p), pulse duration $\boldsymbol{\tau_b\omega_p=60}$.

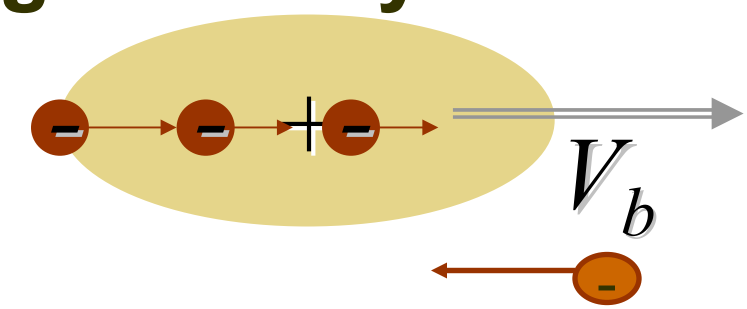
Criterion for neutralization is long pulse duration $\boldsymbol{\tau_b\omega_p>>1}$.

Two ways for ion beam pulse to grab electrons to insure full neutralization.

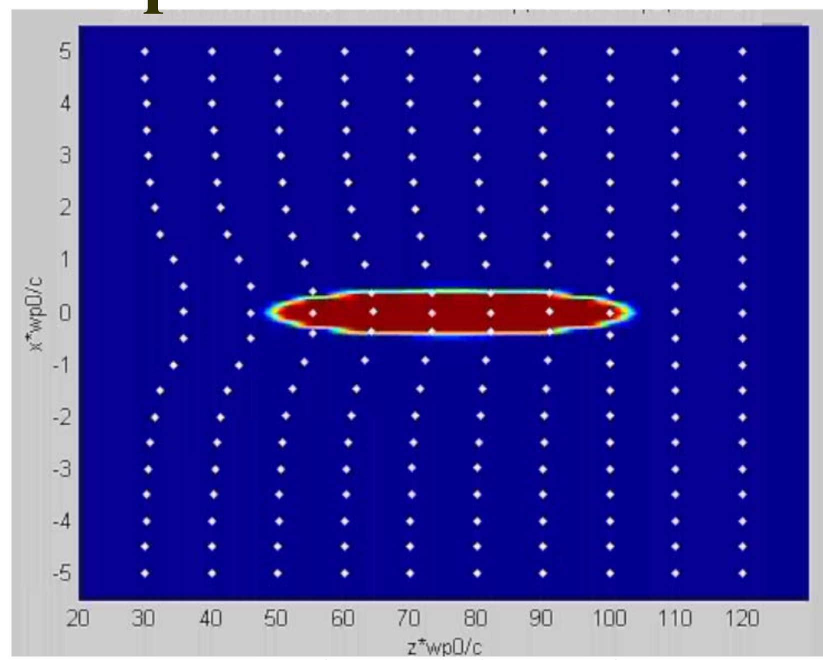
Transversely



Longitudinally

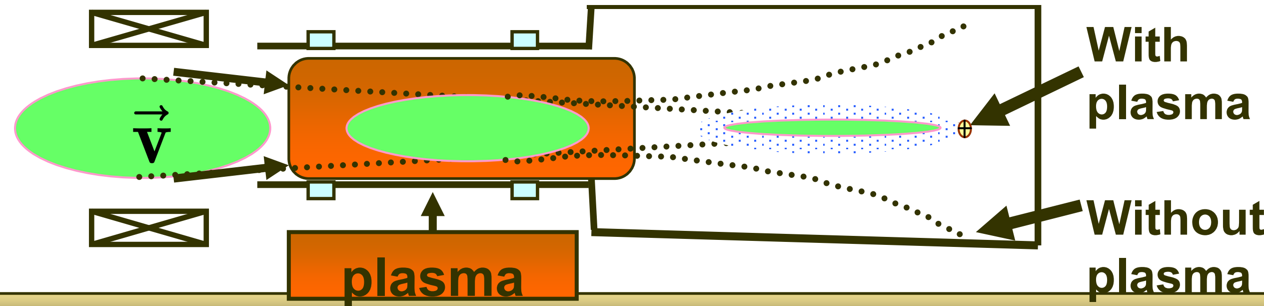


Electron positions in response to ion bunch



Note in unneutralized beam pulses, electrons accelerate into the beam attracted by space potential: indicating the inductive field is important even for slow beams!

Outline



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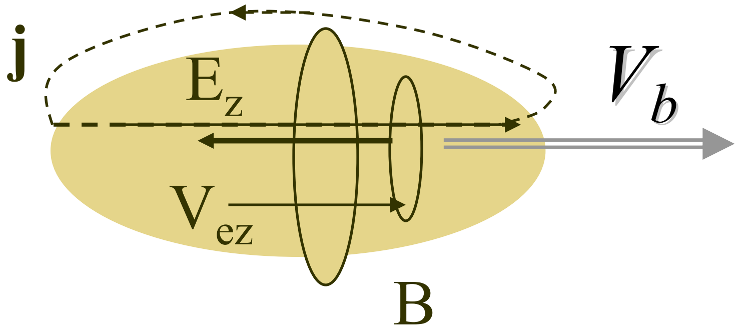
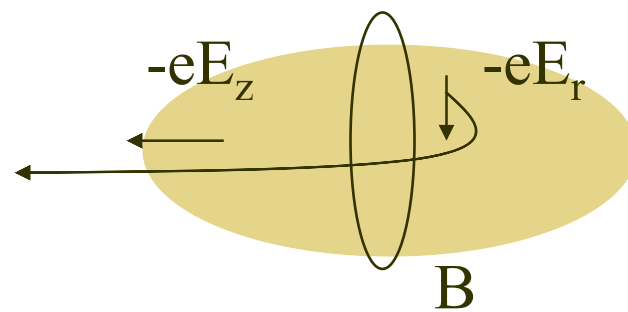
Electrons produced in the beam pulse carry away magnetic field

Electrons enter ahead of the beam pulse $$v_{ez} = \frac{eA_z(z)}{mc}$$



Electrons originate inside the beam pulse

$$v_{ez} = \frac{e}{mc}\left[A_z(z) - A_z(z_b)\right]$$

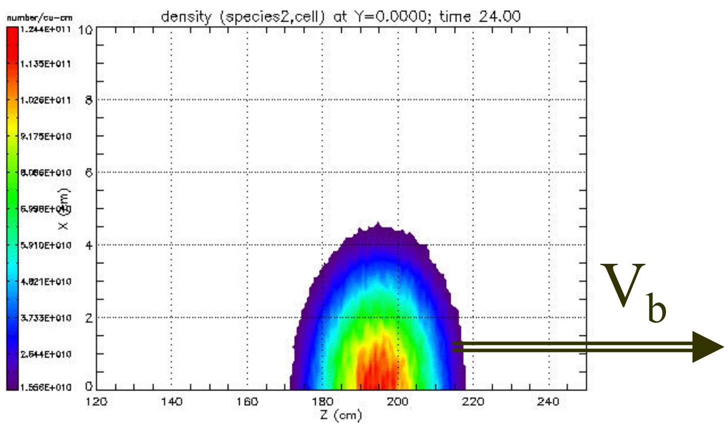


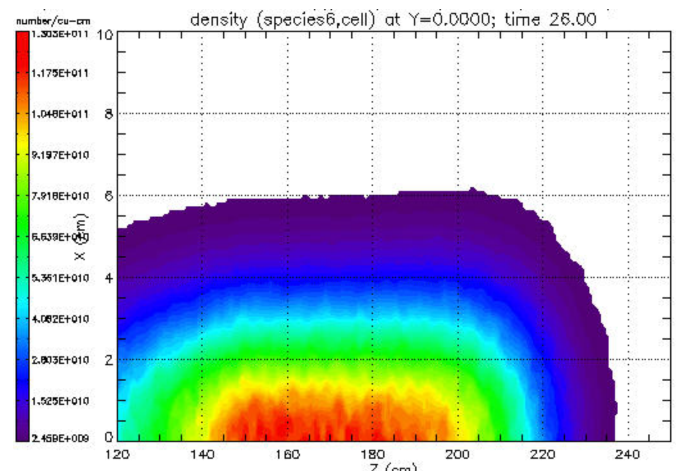
If an electron originates in the region of strong magnetic field, and later moves into a region of weaker magnetic field, then the electron flow velocity is in the direction opposite to the beam velocity; and the current of such electrons *enhances* the beam current rather than diminishes the beam current.

The return current becomes nonlocal.

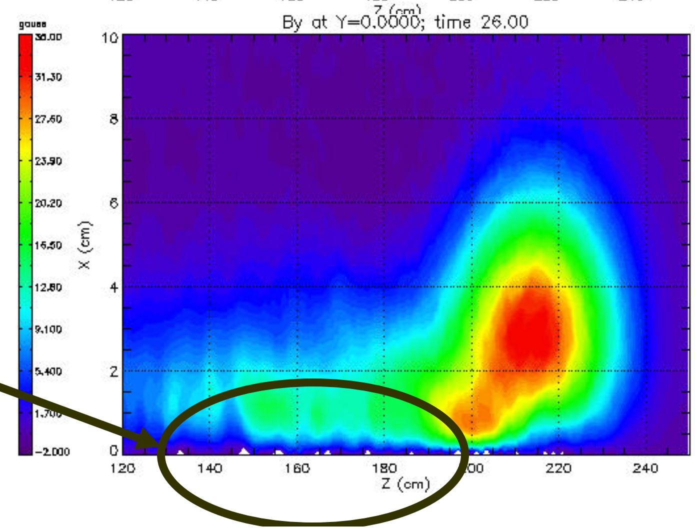
Long tail in the B profile is produced in the wake of the beam pulse due to ionization.

Beam pulse (left) produces plasma by gas ionization with comparable density (right), which generates a tail in the self-magnetic field.





E_x in the beam pulse pushes new electrons into the beam center. E_z in the beam tail pushes electrons in the direction opposite to the beam velocity.



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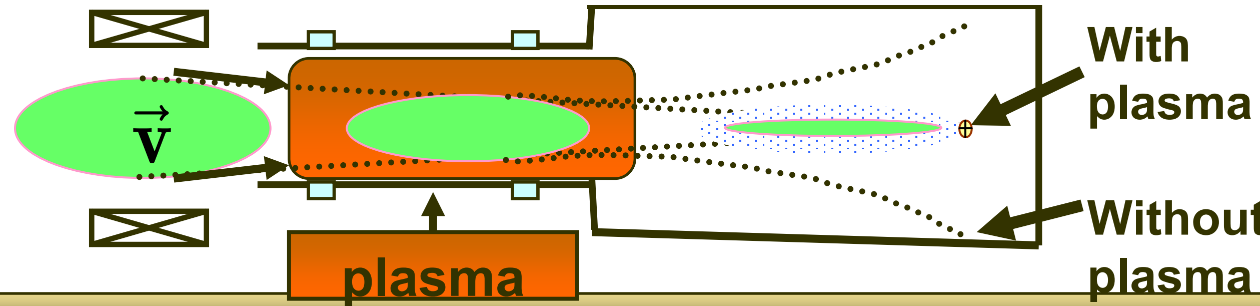

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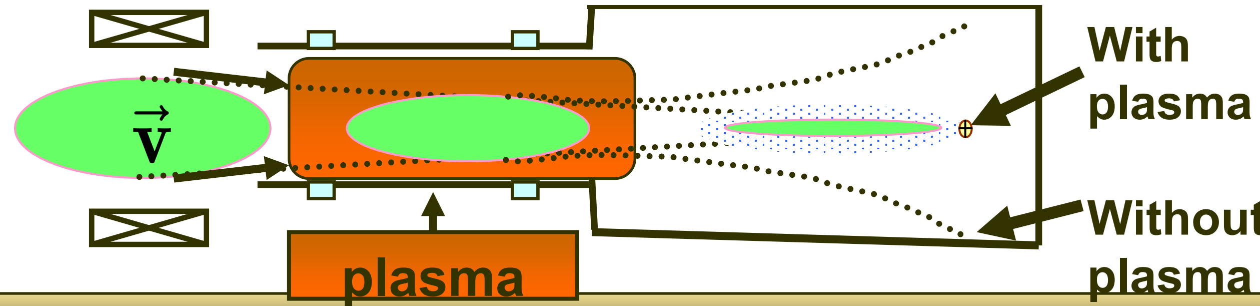
  - Degree of current neutralization
-
- **Effects of applied magnetic field**
  - **Solenoidal field along beam propagation**
  - Dipole field across beam propagation
- Transients (entry to and exit from plasma)

Outline



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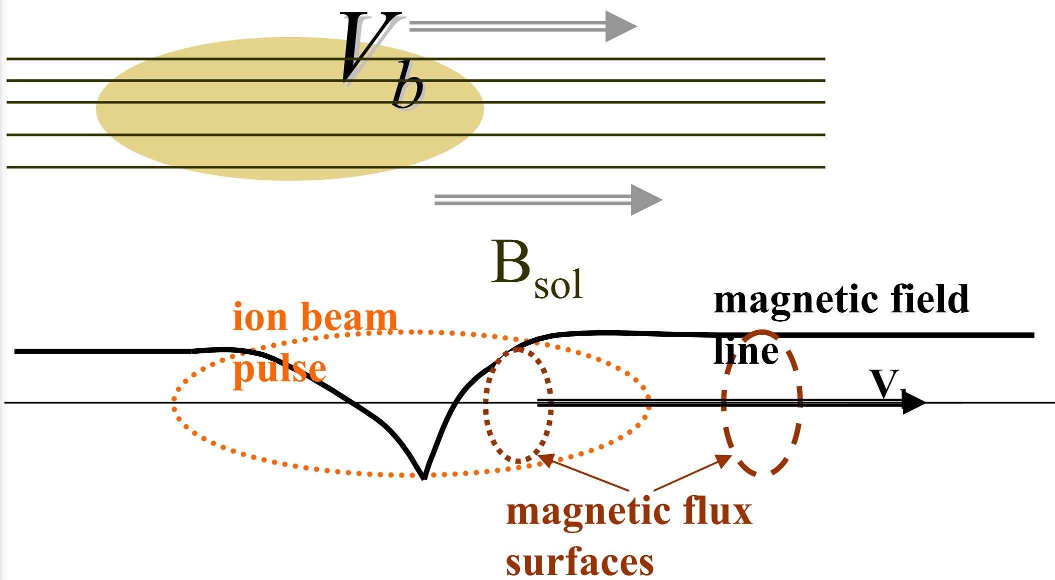
Influence of magnetic field on beam neutralization by a background plasma



$$\frac{\partial \vec{p}_e}{\partial t} + (\vec{V}_e \bullet \nabla)\vec{p}_e = -\frac{e}{m}(\vec{E} + \frac{1}{c}\vec{V}_e \times \vec{B}),$$

Small radial electron displacement generates fast poloidal rotation according to conservation of azimuthal canonical momentum:

$$V_\phi = \frac{e}{mc}(A_\phi + B_{sol}\delta r)$$

$$E_r \sim \frac{1}{c} V_{e\phi} B_{sol}$$

$$B_{e\varphi} = B_{ez}\frac{V_{e\varphi}}{V_{bz}}$$

The poloidal rotation twists the magnetic field and generates the poloidal magnetic field and large radial electric field.

I. Kaganovich, et al, PRL **99**, 235002 (2007); PoP (2008).

Equations for Vector Potential in the Slice Approximation.

$$-\frac{1}{r}\frac{\partial}{\partial r}r\frac{\partial}{\partial r}A_z = \frac{4\pi}{c}j_{bz} - \frac{\omega_{pe}^2}{c^2}A_z - \frac{\omega_{ce}}{V_b}\frac{1}{r}\frac{\partial}{\partial r}(rA_\phi).$$

$$-\left(1+\frac{\omega_{ce}^2}{\omega_{pe}^2}\right)\frac{\partial}{\partial r}\left[\frac{1}{r}\frac{\partial}{\partial r}(rA_\phi)\right] = \frac{4\pi}{c}j_{b\phi} - \frac{\omega_{pe}^2}{c^2}A_\phi - \frac{\omega_{ce}}{V_b}\frac{\partial}{\partial r}A_z.$$

The electron return current

New term accounting for departure from quasi-neutrality.

Magnetic dynamo

Electron rotation due to radial displacement

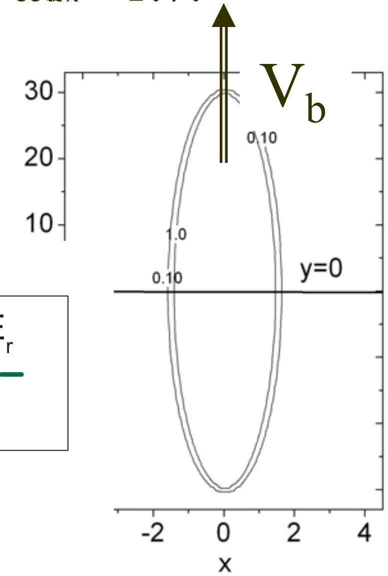
$$\omega_{ce} = \frac{eB_z}{mc}$$

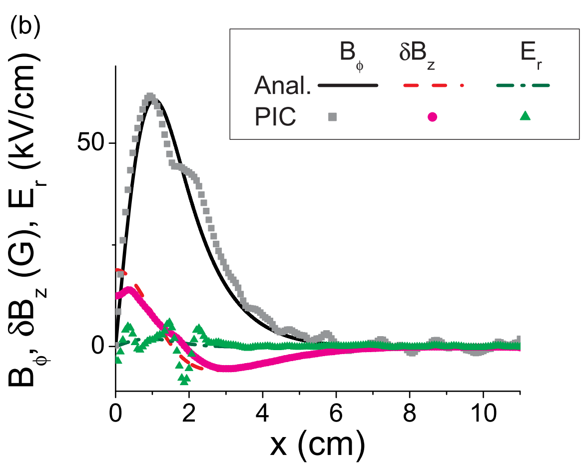
I. Kaganovich, et al, PRL **99**, 235002 (2007).

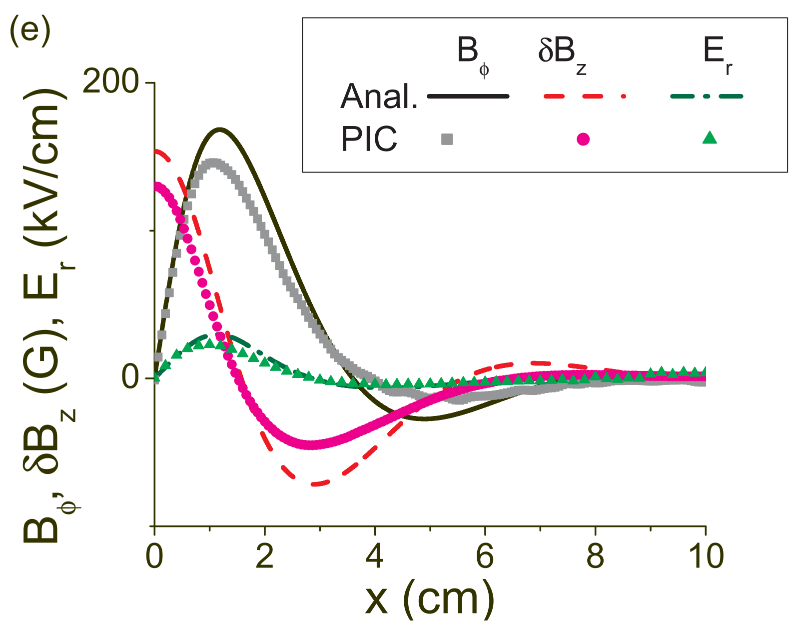
Applied magnetic field affects self-electromagnetic fields when $\omega_{ce}/\omega_{pe} > V_b/c$

The self-magnetic field; perturbation in the solenoidal magnetic field; and the radial electric field in a perpendicular slice of the beam pulse. The beam parameters are (a) $n_{b0} = n_p/2 = 1.2 \times 10^{11} cm^{-3}$; $V_b = 0.33c$, the beam density profile is gaussian. Applied B_{z0} (b) 300G; $c\omega_{ce}/V_b\,\omega_{pe} = 0.57$ and (e) 900G; $c\omega_{ce}/V_b\,\omega_{pe} = 1.7$.

Note increase of fields with applied magnetic field B

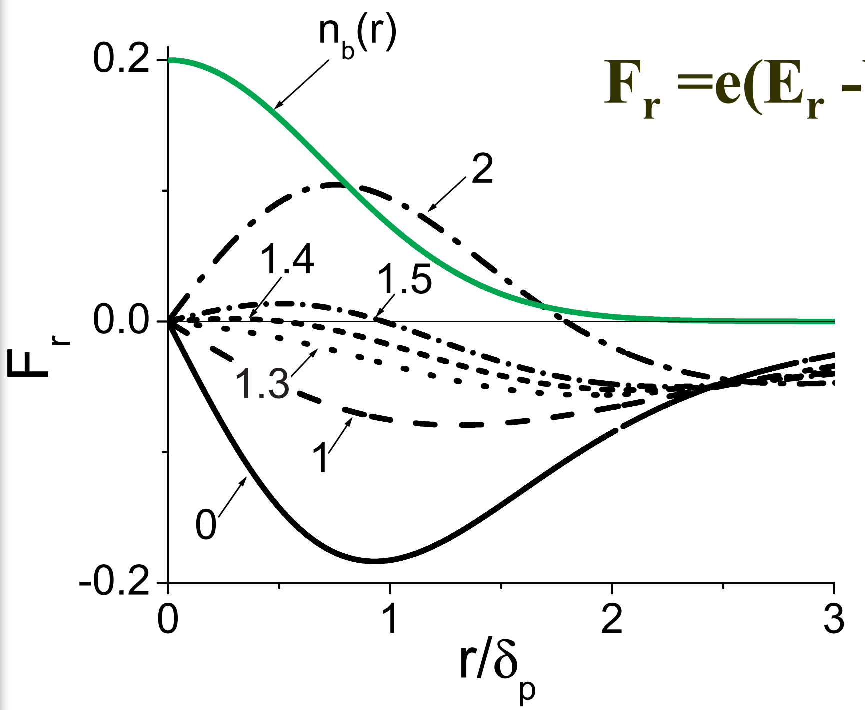




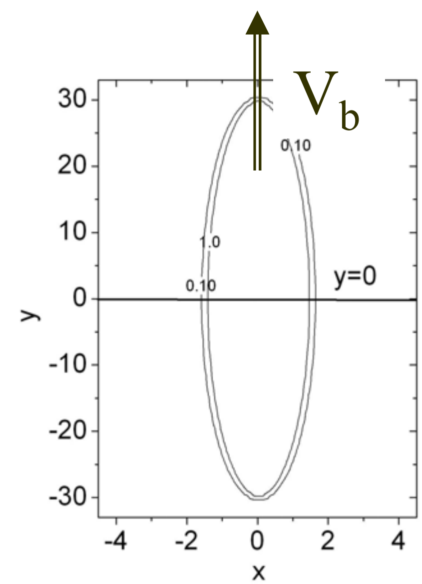


Application of the solenoidal magnetic field allows control of the radial force acting on the beam ions.

Normalized radial force acting on beam ions in plasma for different values of $(\omega_{ce} / \omega_{pe}\beta_b)^2$. The green line shows a gaussian density profile. $r_b = 1.5\delta_p$; $\delta_p = c/\omega_{pe}$.

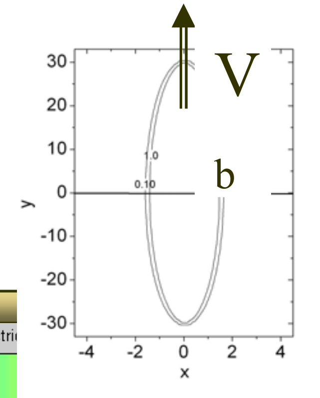


$$\mathbf{F_r = e(E_r - V_b B_\varphi / c),}$$



I. Kaganovich, et al, PRL **99**, 235002 (2007).

Plasma response to the beam is drastically different depending on $\omega_{ce}/2\beta_b\omega_{pe}$ <1 or >1



Gaussian beam:
$r_b=2c/\omega_{pe}$, $l_b=5r_b$,
β_b =0.33.

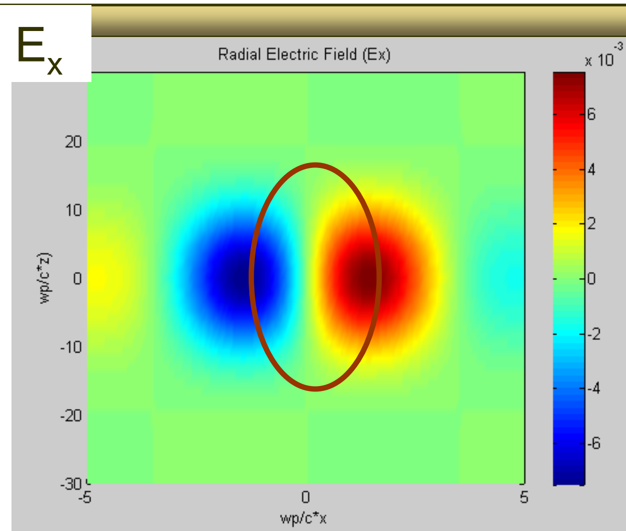
Brown line indicate the ion beam pulse.

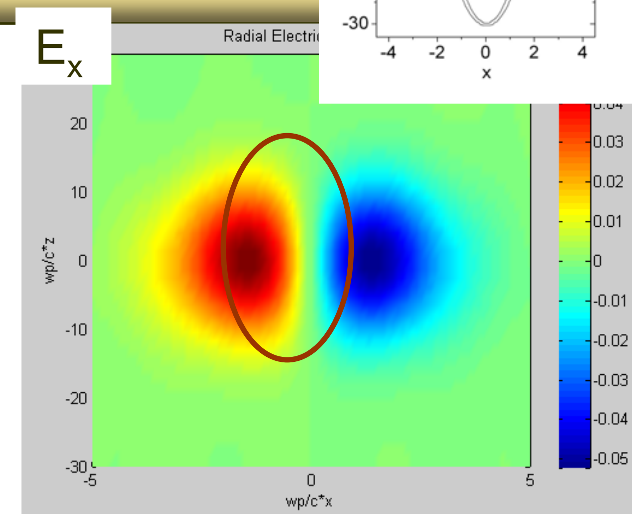
$\omega_{ce}/2\beta_b\omega_{pe}$

Left: 0.5

Right: 4.5

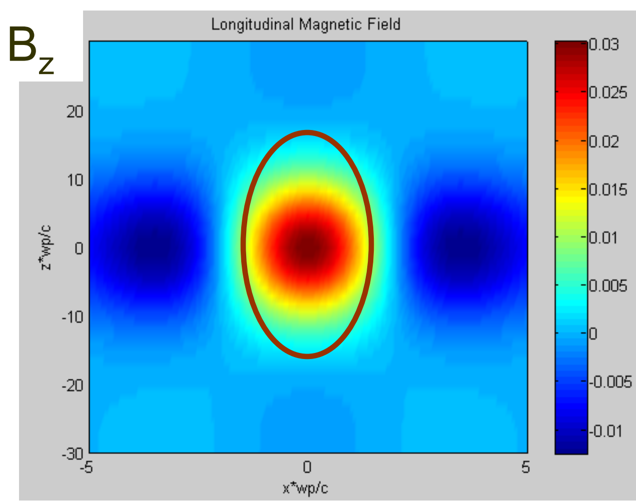
M. Dorf, et al, submitted PoP (2009).

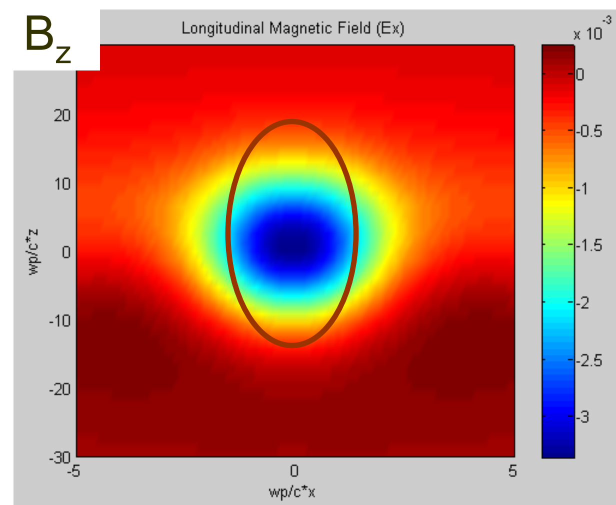




Electrostatic field is defocusing
The response is paramagnetic

Electrostatic field is focusing
The response is diamagnetic





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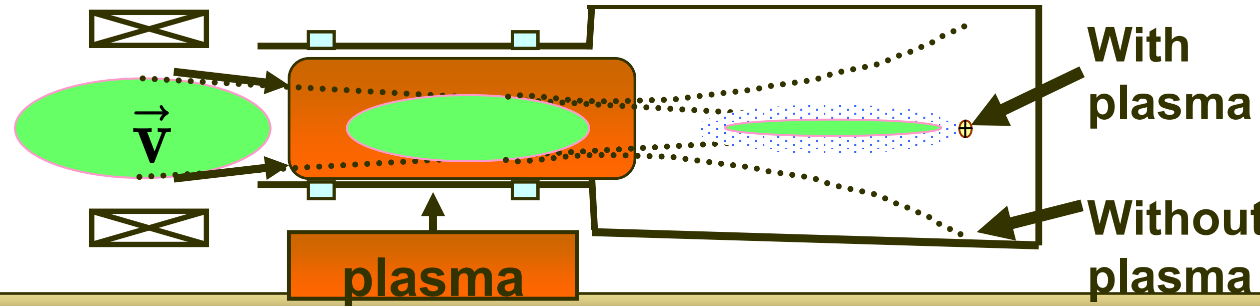

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  - **Wave excitation**
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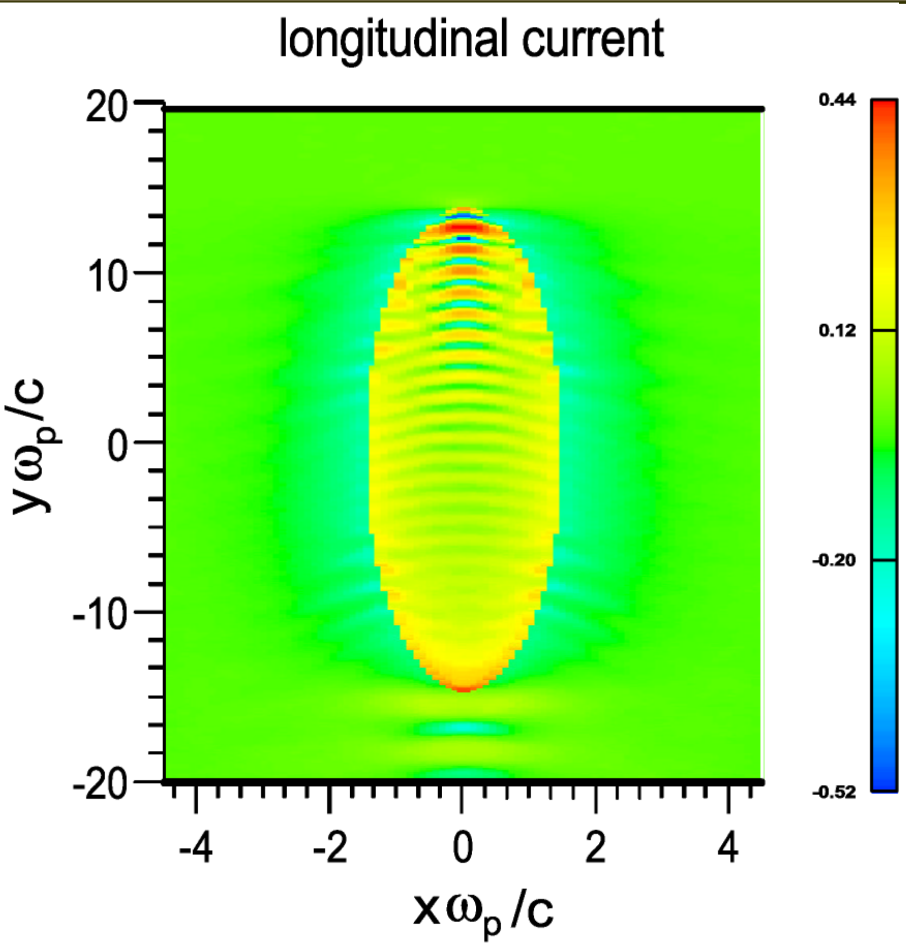
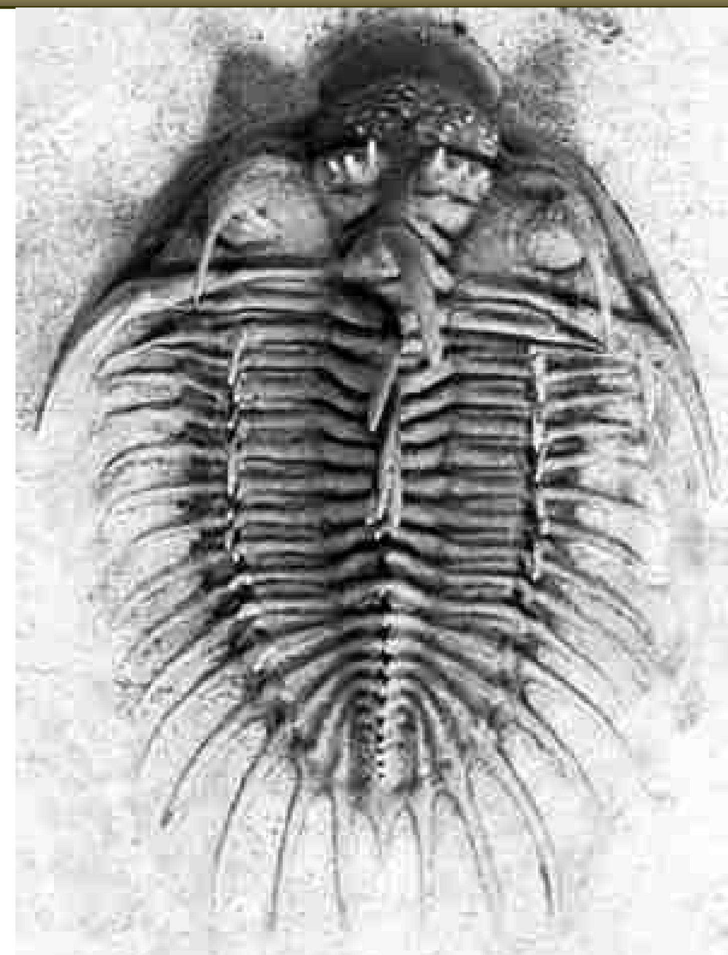
Excitation of plasma waves by the short rise in the beam head.



normalized electron current $j_y/(ecn_p)$

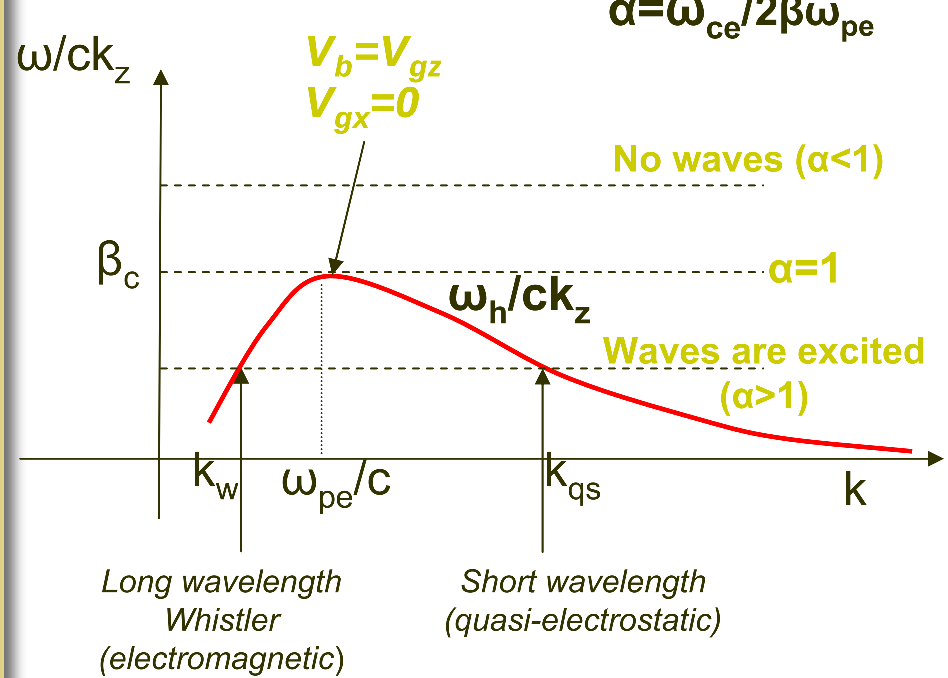


http://www.trilobites.com

Electromagnetic Field Radiation by a Moving Beam in a Magnetized Plasma

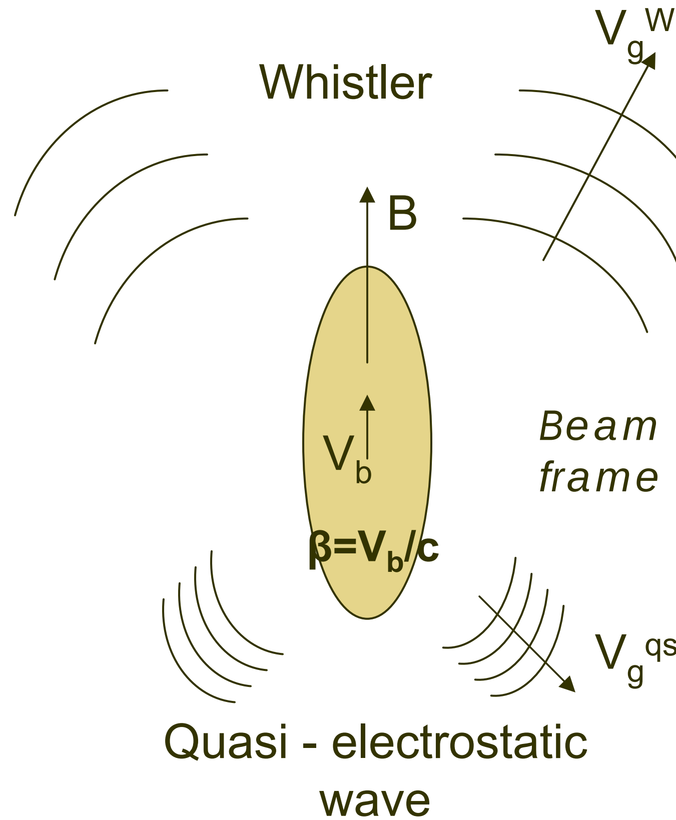
- Beam excites/radiates Helicon (electron) branch $\omega_h = \omega_{ce} k k_z \Big/ \left(k^2 + \dfrac{\omega_{pe}^2}{c^2} \right)$ *assumed $\omega_{ce} << \omega_{pe}$ for simplicity*

$\alpha = \omega_{ce} / 2\beta\omega_{pe}$



$V_{gz} > V_b$ $\qquad$ $V_{gz} < V_b$

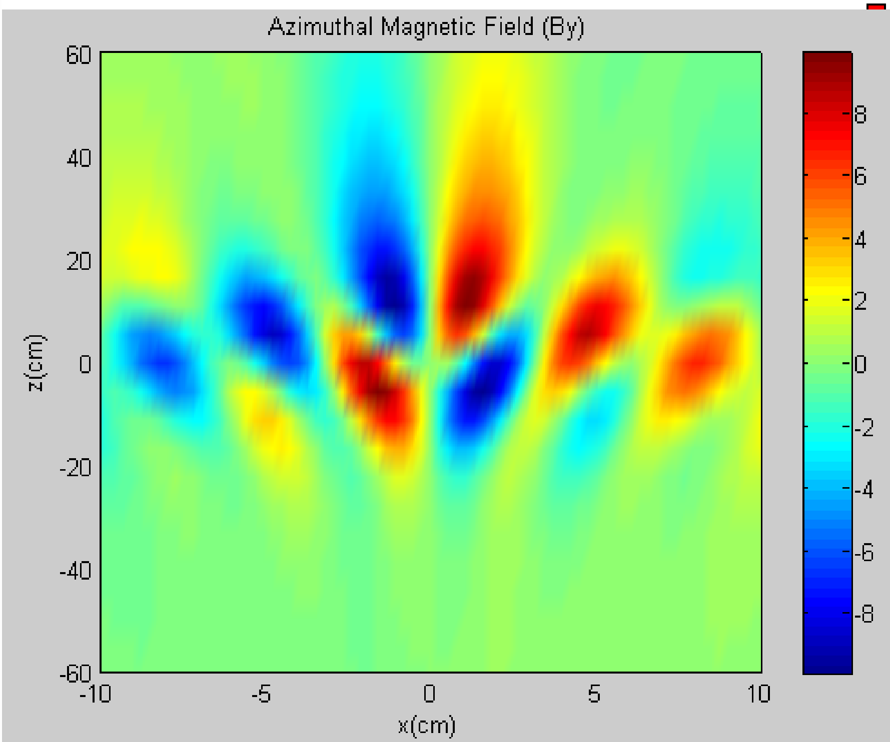
$k_z V_{gx} > 0$ $\qquad$ $k_z V_{gx} < 0$



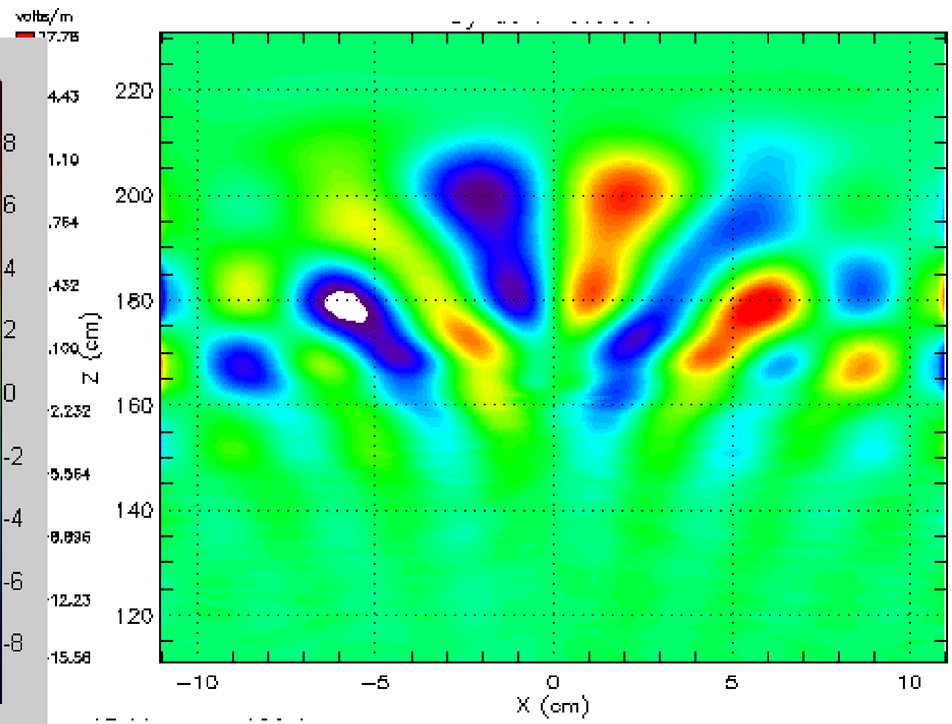
Beam pulse can excite whistler waves.

Gaussian beam with *β=0.33, l_b=17r_b, r_b=ω_p/c n_b=0.05n_p,* $\omega_{ce}/2\beta_b\,\omega_{pe}$=1.37

Analytical theory



PIC



Courtesy of J. Pennington and M. Dorf

Conclusions for neutralization

Developed a nonlinear theory for the quasi-steady-state propagation of an intense ion beam pulse in a background plasma

- for charge neutralization key parameter is $\omega_p l_b/V_b$,
- for current neutralization: key parameter $\omega_p r_b/c$.

The background plasma can provide the necessary neutralization for compression, provided the plasma density exceeds the beam density everywhere along the beam path, i.e., $n_p>n_b$.

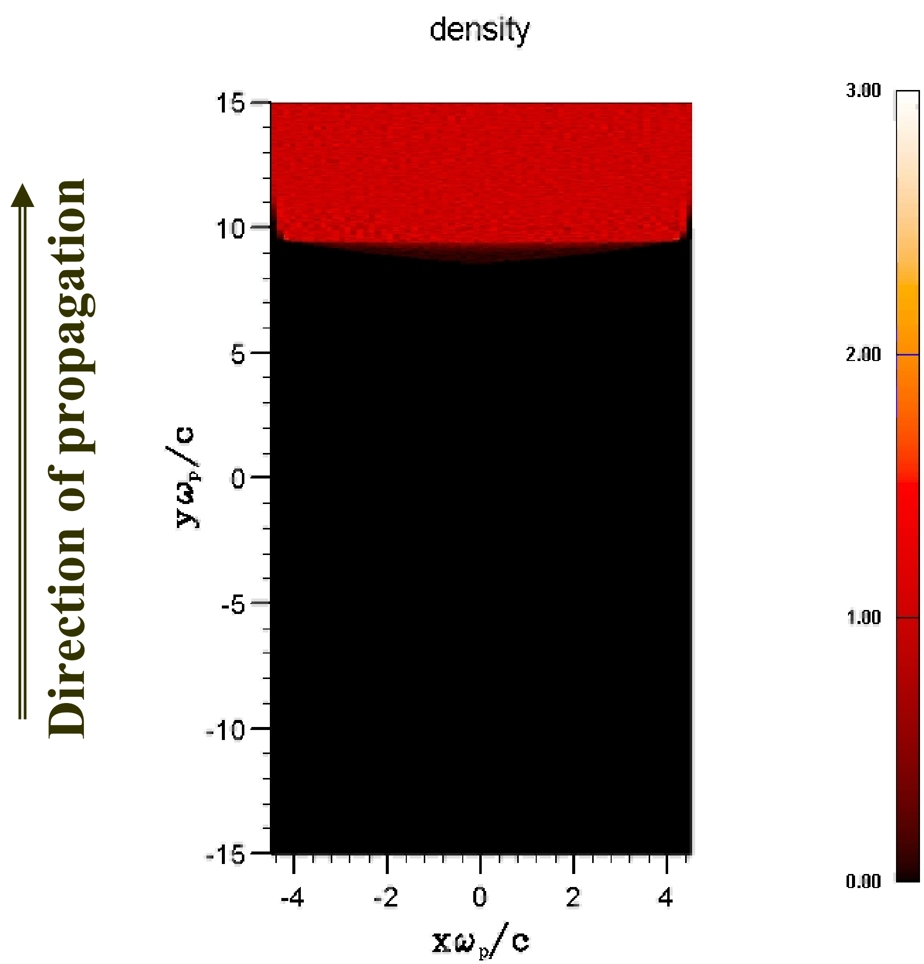
Application of a solenoidal magnetic field can be used for active control of beam transport through a background plasma.

- Theory predicts that there is a sizable enhancement of the self-electric and self-magnetic fields where $\omega_{ce}\sim\beta\omega_{pe}$.
- Electromagnetic waves are generated oblique to the direction of the beam propagation where $\omega_{ce}>2\beta\omega_{pe}$.

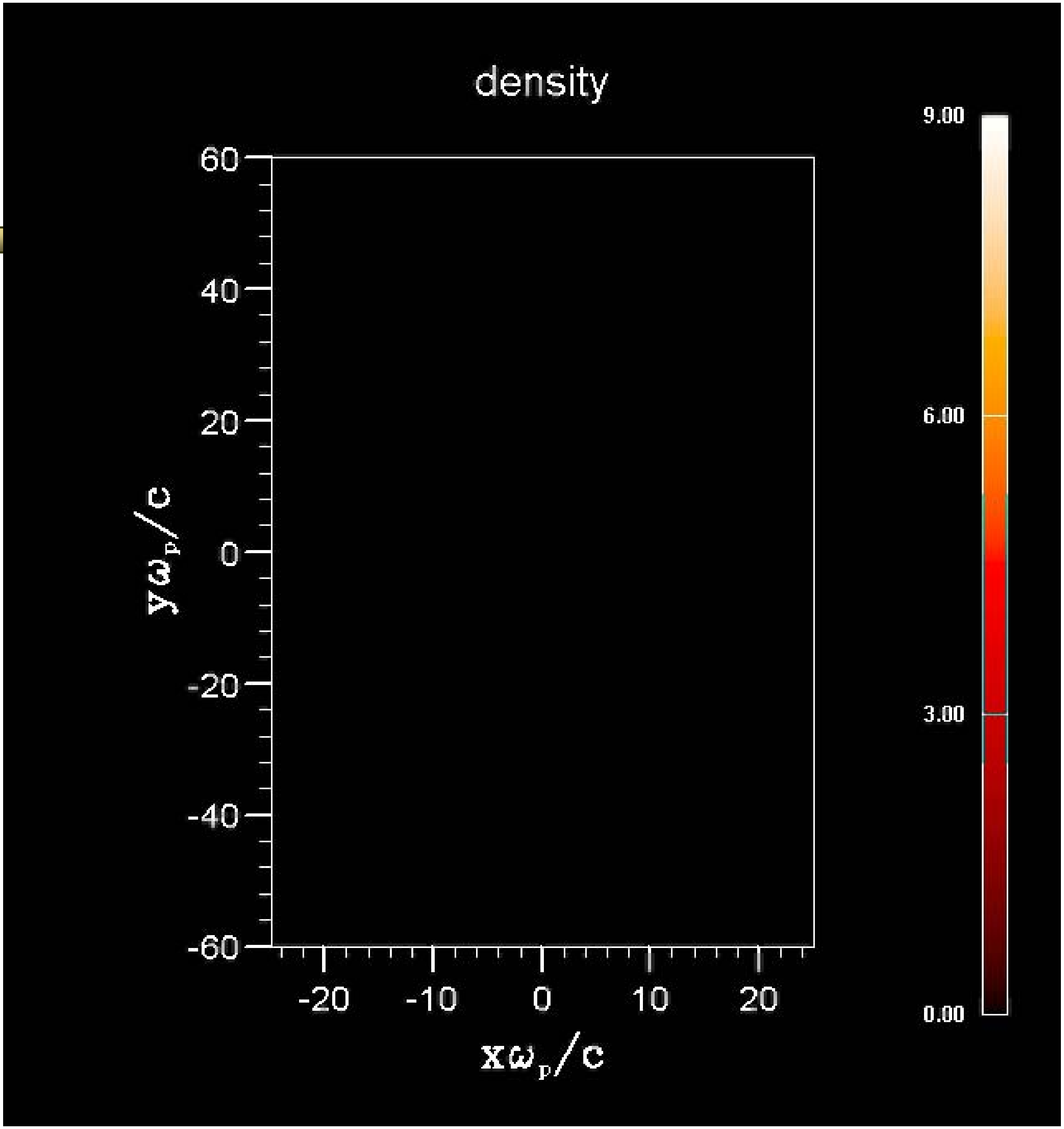
Results of neutralization from 2D PIC Code

Shown are electron density.

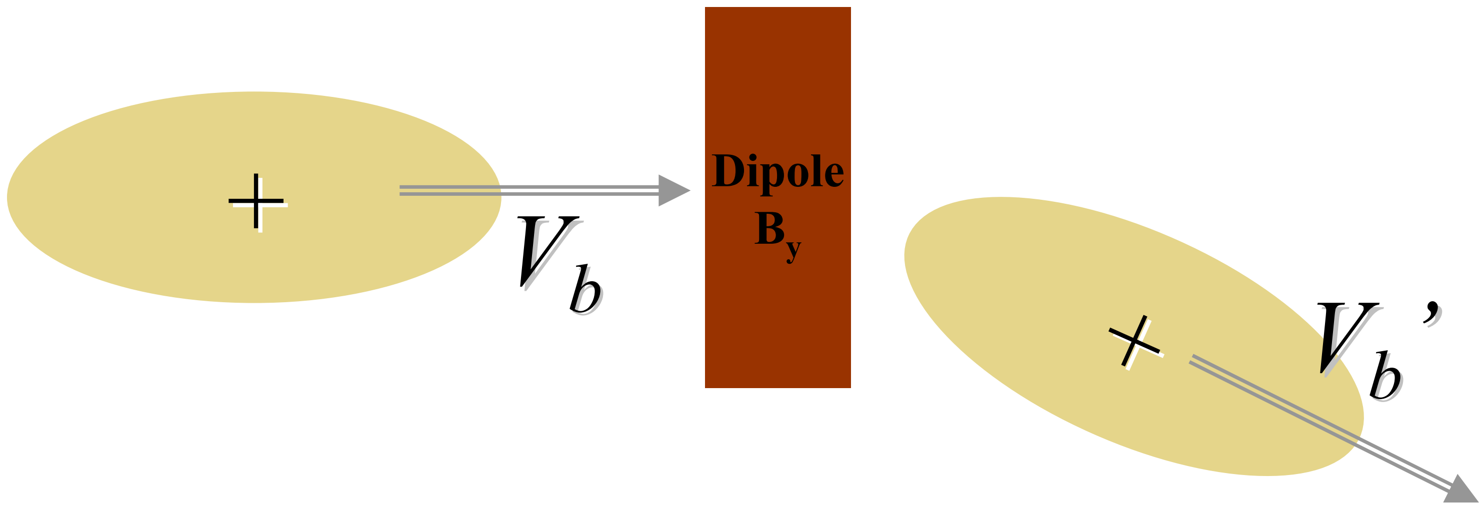
Beam propagation in the y-direction,
beam length 7.5 c/ω_p;
beam radius 1.5 $c/\ \omega_p$;
beam density equals to the half of the plasma density;
beam velocity $c/2$.



beam length 30. c/ω_p; beam radius 0.5 c/ω_p;
•beam density is 5 of plasma density;
•beam velocity 0.5c.



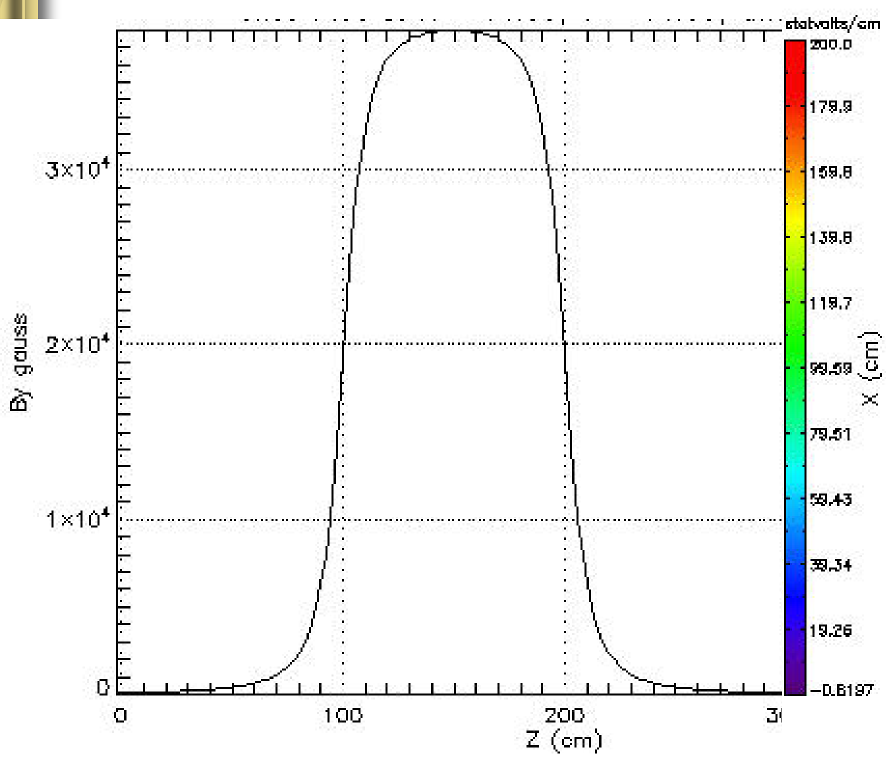
Dipole magnetic field can be used to deflect ion beam motion

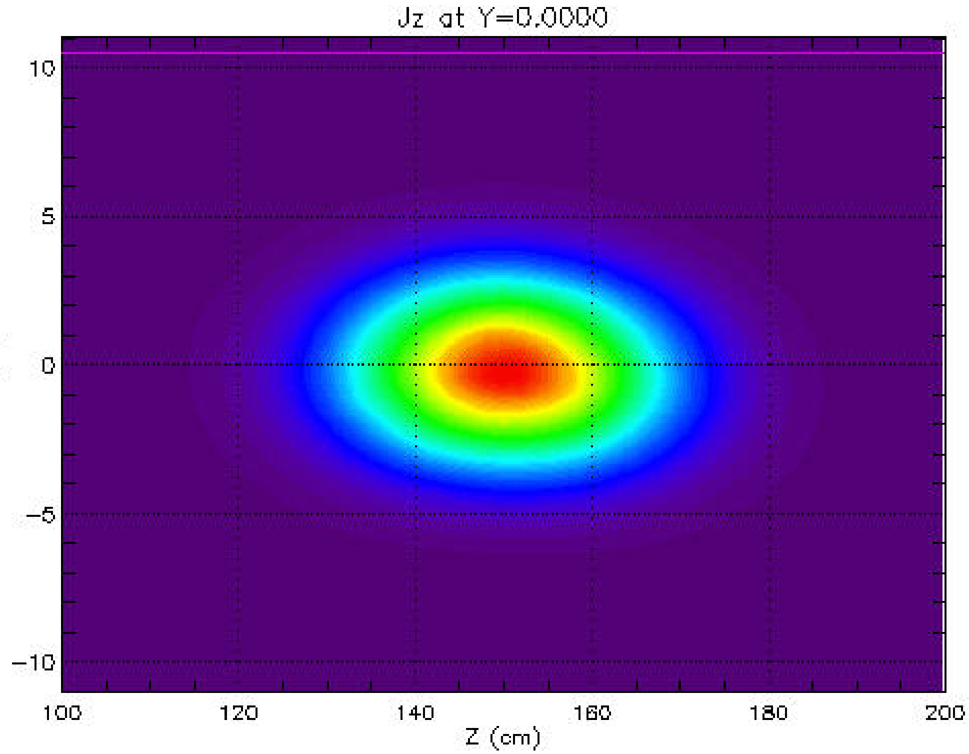


- Can plasma still neutralize the beam in a strong magnetic field?
- 3D simulations are needed!

3D simulations show no current neutralization

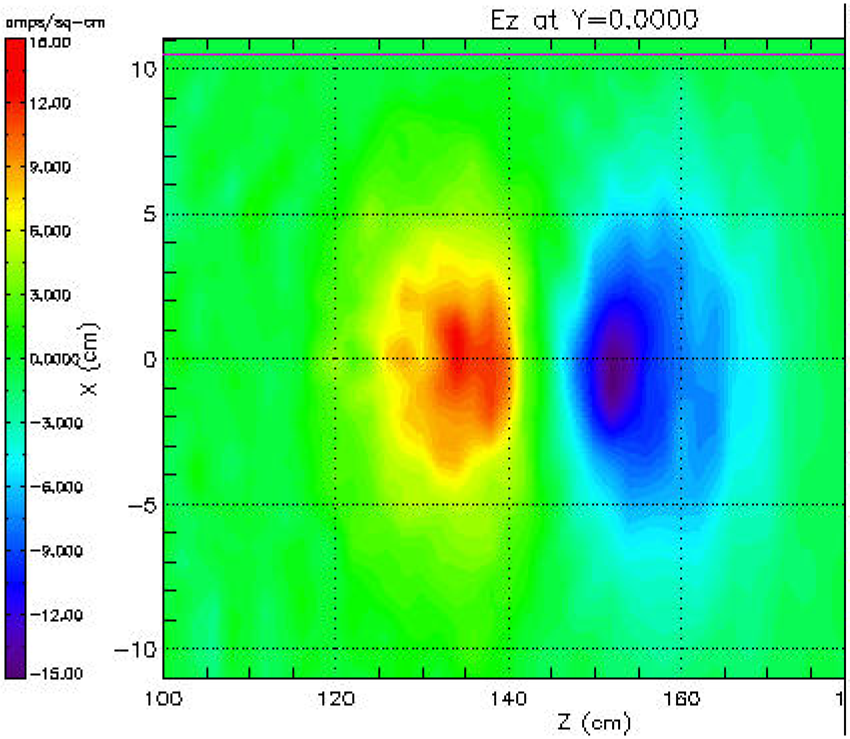
Shown are the magnetic field of the dipole, B_y *and* the current density in the dipole region, j_z;

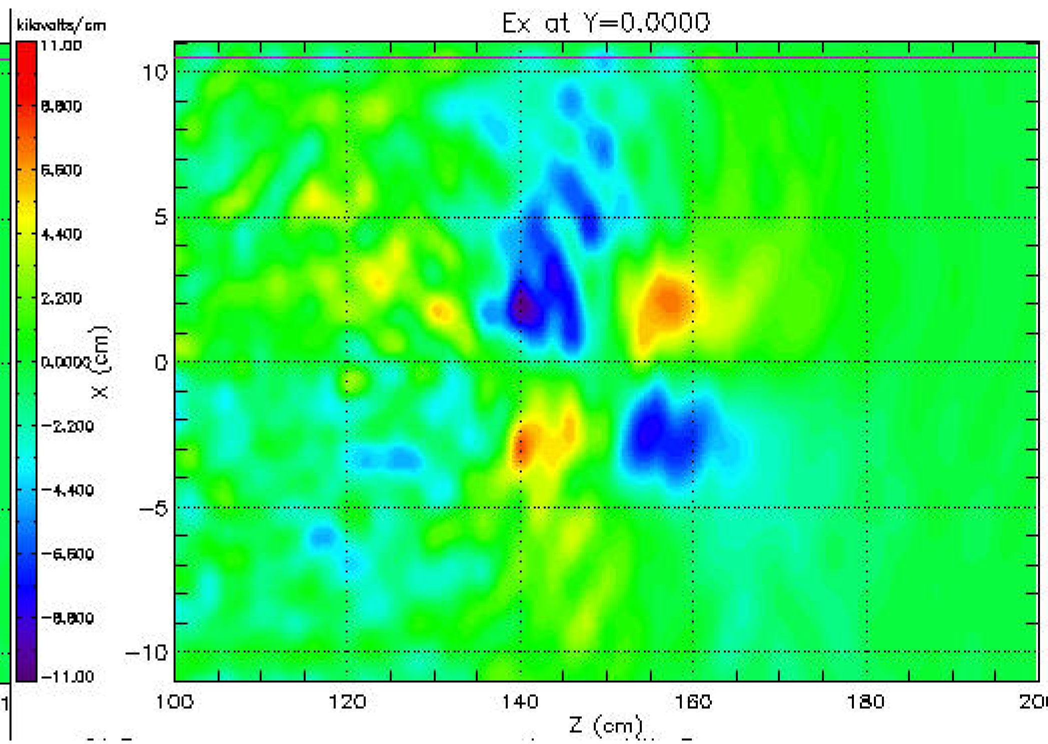




3D simulations show good charge neu-tralization and quadrupole structure of E_x

Shown are the longitudinal, inductive electric field, *E_z, and* the transverse electric field, *E_x*.

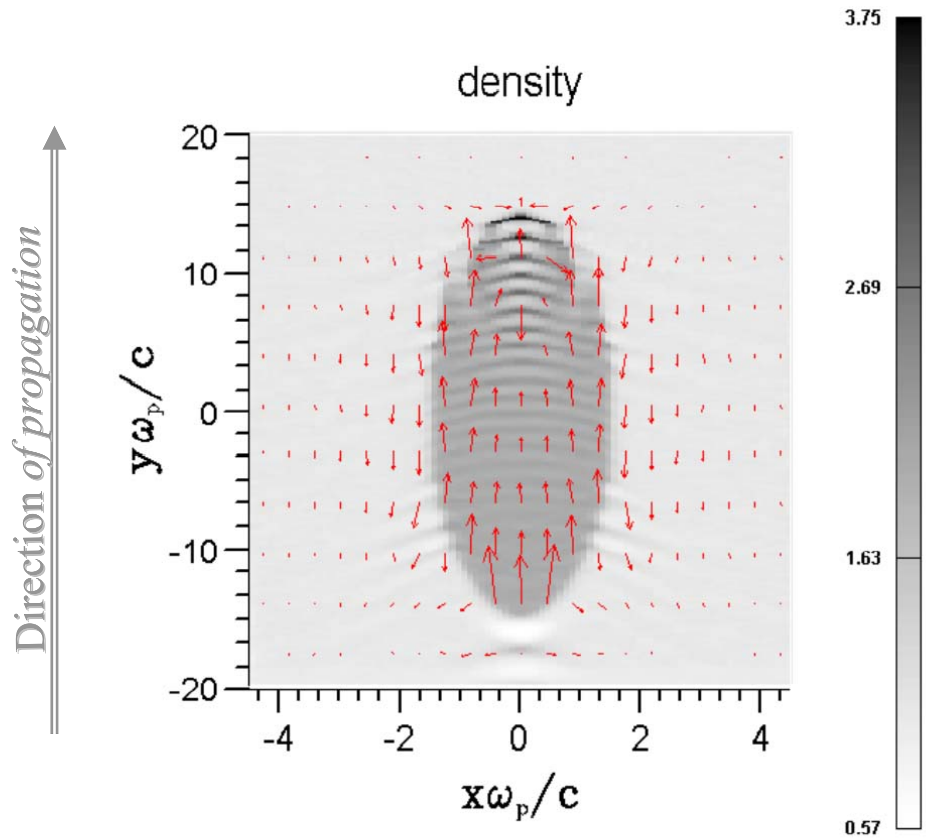




Steady- State Results (current flow)

Beam propagates in the y-direction,
beam half length l_b=15 c/ω_p ;
beam radius r_b =1.5 c/ω_p ;
beam density n_b is equal to the background plasma density n_p;
beam velocity V_b=$c/2$.

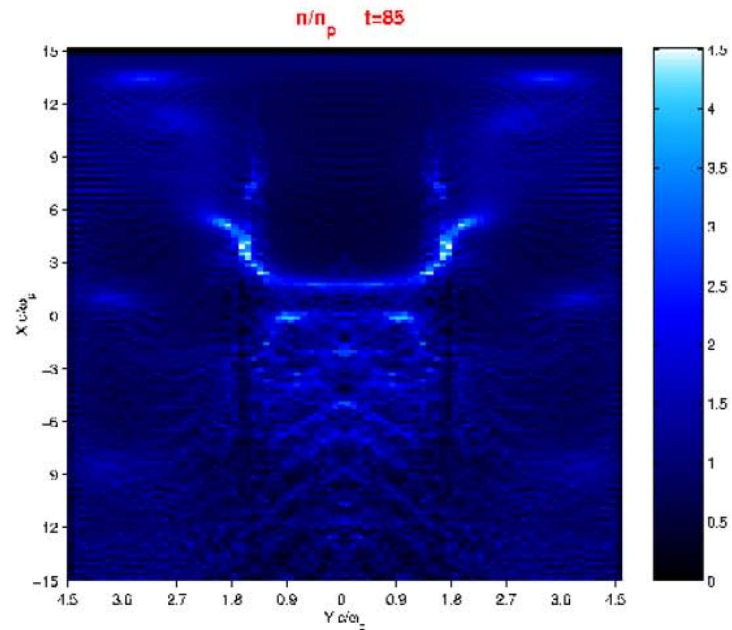
Shown are the normalized electron density n_e/n_p and the vector fields for the current.

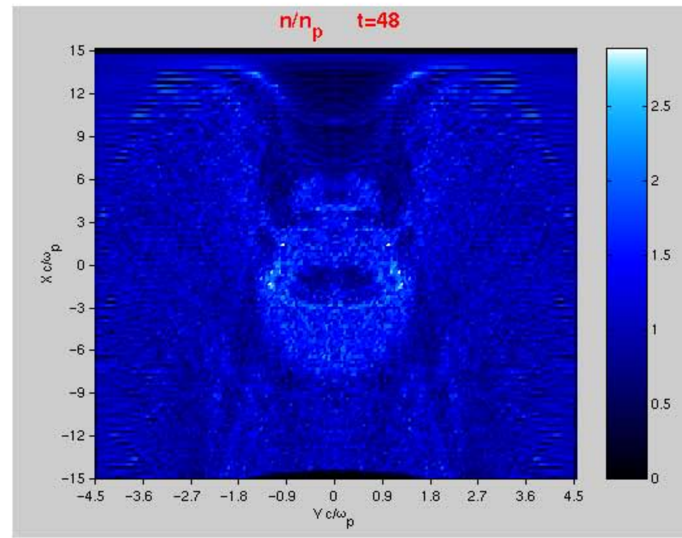


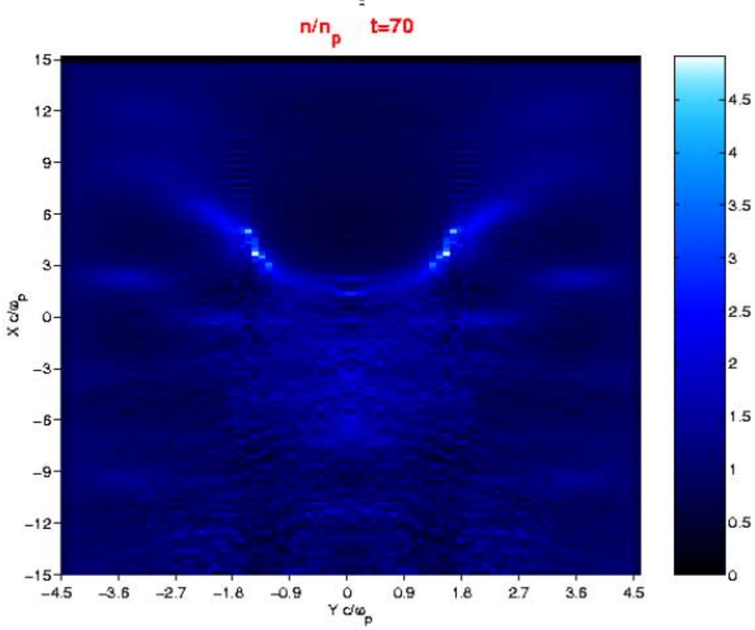
FOR MORE INFO...

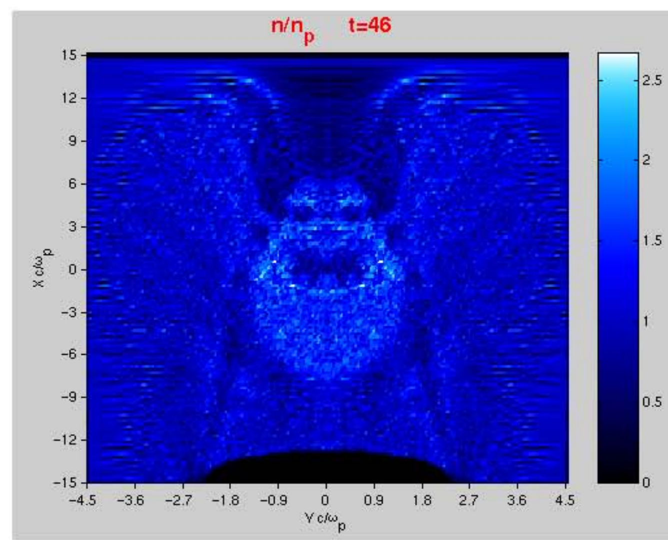
http://hifnews.lbl.gov/hifweb08.html

Beam Propagates Along Magnetic Field.









Comparison of Theory and Simulation: Electron Density

Key parameter $\omega_p l_b/V_b$,

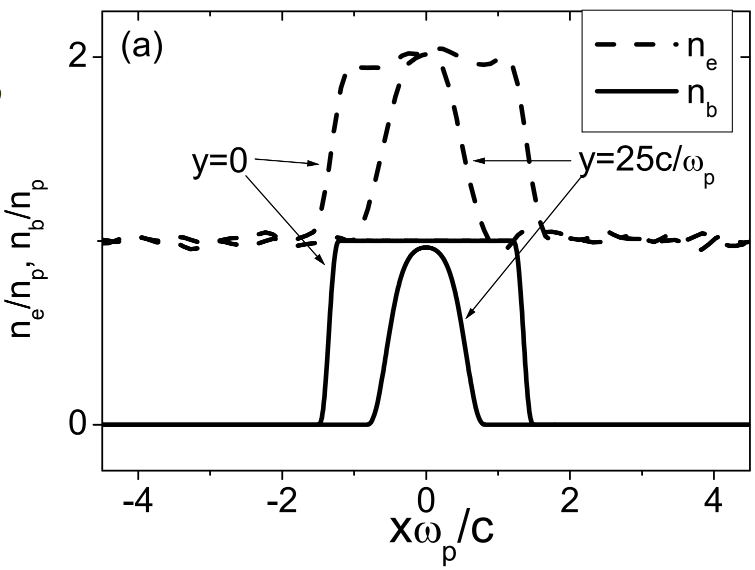
Quasineutrality $l_b >> V_b / \omega_p$.

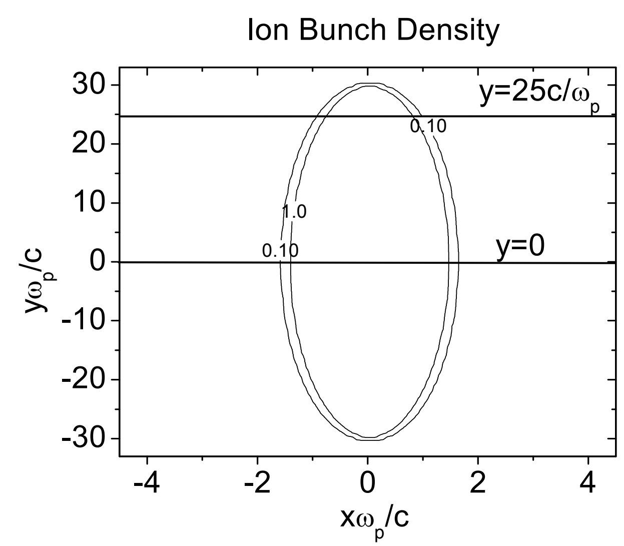
$l_b = 30c/\omega_p$

$r_b = 1.5c/\omega_p$

$n_p = n_b$

$V_b = 0.5c$





Comparison of Theory and Simulation: Magnetic Field

Key parameter $\omega_p r_b/c$,

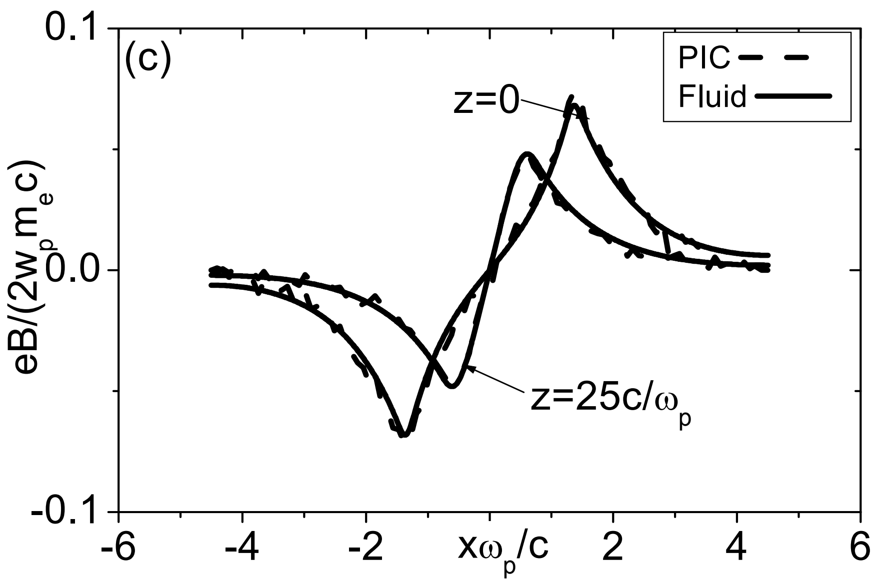
Magnetic field neutralization $r_b >> c/\omega_p$.

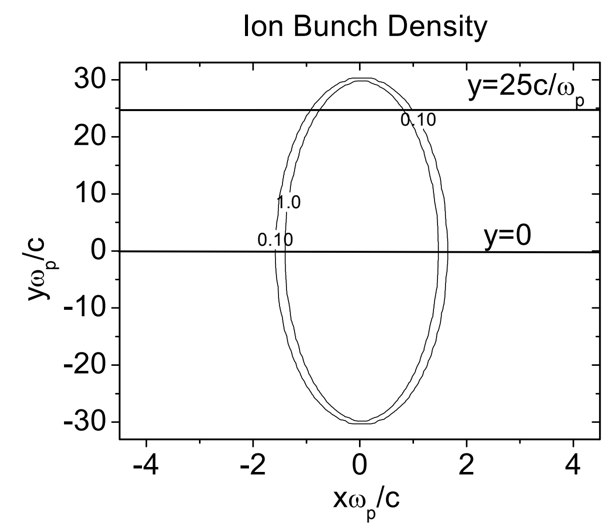
$l_b = 30c/\omega_p$

$r_b = 1.5c/\omega$

$n_p = n_b$

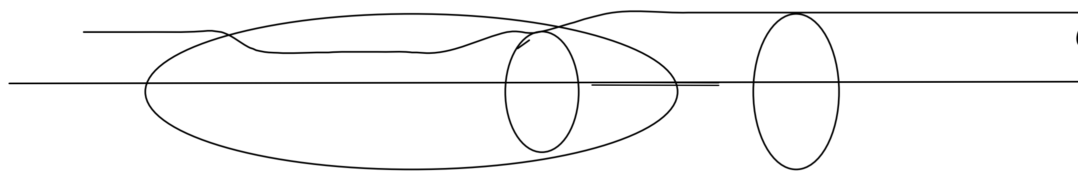
$V_b = 0.5c$





FOR MORE INFO... I. Kaganovich, *et.al*, Physics of Plasmas 8, 4180 (2001).

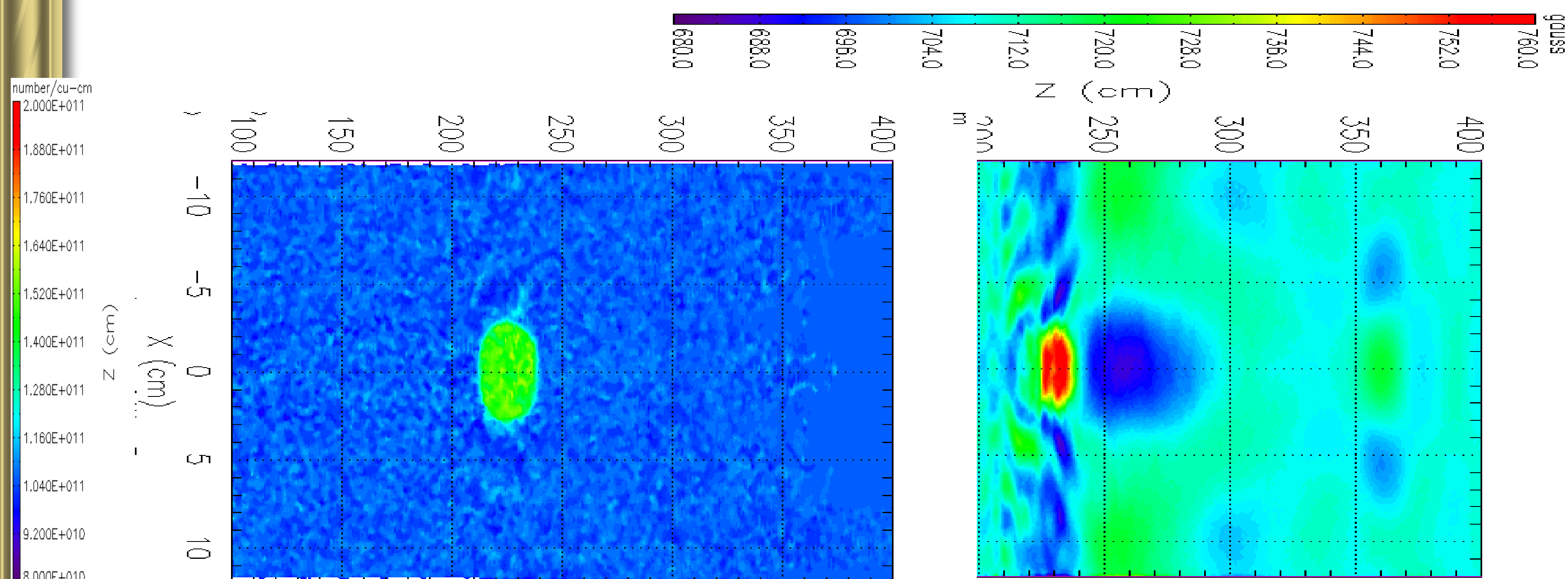
Plasma acts as a paramagnetic medium inside the ion beam pulse due to induced electron rotation!



$$\delta B_z = -B_z \delta S / S$$

$$\delta B_z \Rightarrow E_\theta \Rightarrow v_\theta$$

Color plot of Beam density and B_z



Comparison of Theory and Simulation: Electron Density

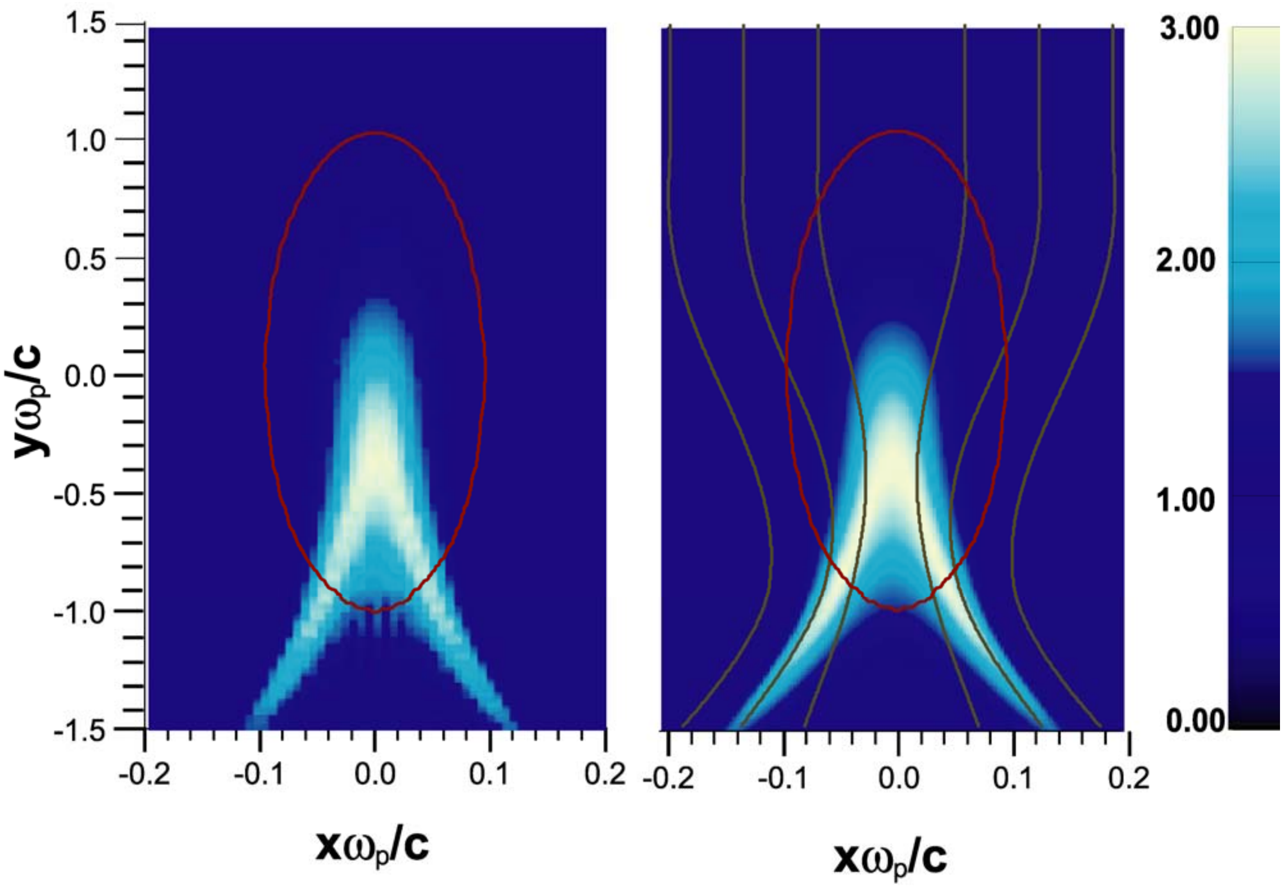
Electron density
Left – PIC,
Right - fluid

$l_b = 1c/\omega_p$, $r_b = 0.1c/\omega_p$

$n_b = 0.5n_p$, $V_b = 0.5c$

Brown lines: electron trajectory in the beam frame.

Red line: ion beam size.

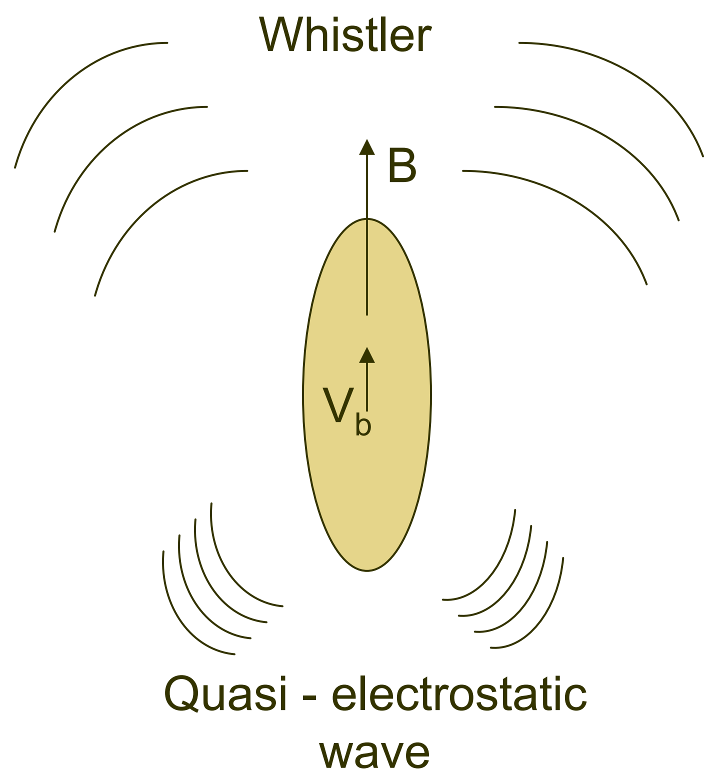


FOR MORE INFO...

I. Kaganovich *et.al*,
http://pacwebserver.fnal.gov/papers/Tuesday/PM_Poster/TPPH317.pdf

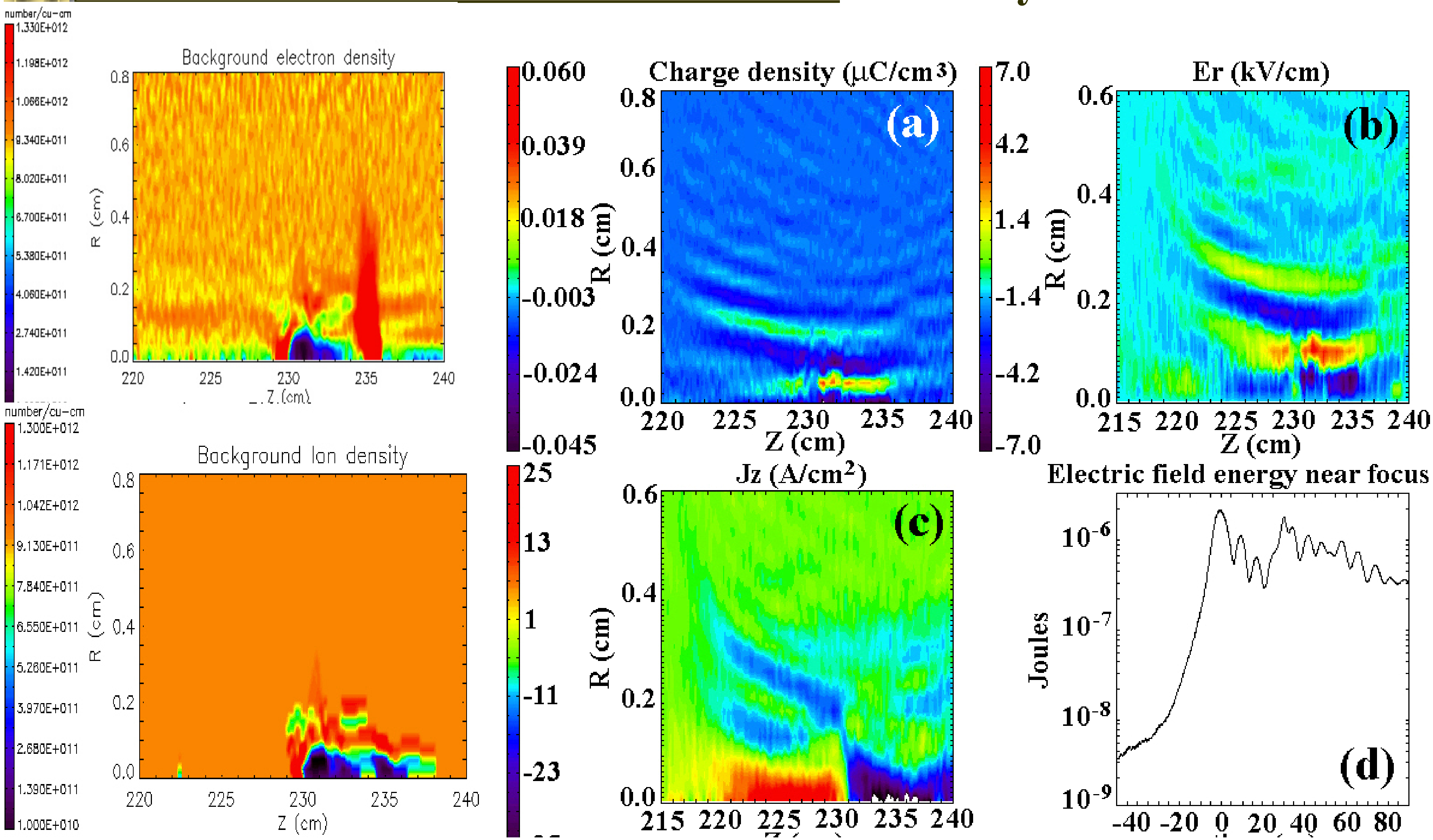
Complicated electrodynamics of beam-plasma interaction would make J. Maxwell proud!

Artist: E.P. Gilson 2008

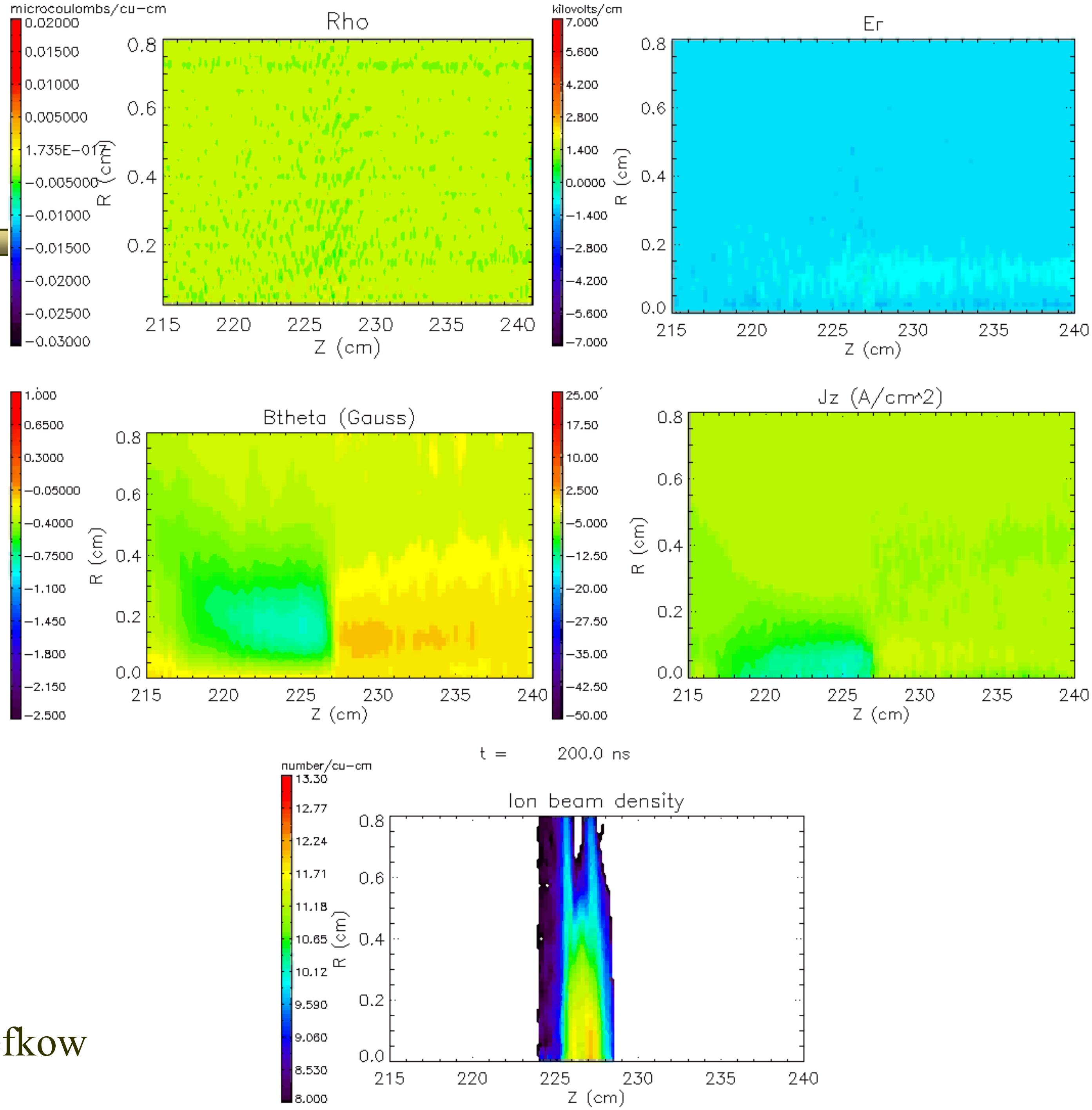


During rapid compression at focal plane the beam can excite lower-hybrid waves if the beam density is less than the plasma density.

Courtesy of A. Sefkow



Movies



Courtesy of A. Sefkow